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STANDARDS AND BENCHMARK TESTS FOR EVALUATING LARGE SCALE MANIPULATORS WITH CONSTRUCTION APPLICATIONS

by

Mark Edward Wiersma

Report

Presented to the Faculty of the Graduate School

of The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

Master of Science in Engineering

The University of Texas at Austin

December 1995

STANDARDS AND BENCHMARK TESTS FOR

EVALUATING LARGE SCALE MANIPULATORS WITH

CONSTRUCTION APPLICATIONS

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Dedicated to the Advancement of Construction Automation

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I would like to thank my new found friends and colleagues for providing guidance, help and companionship over the past year. I particularly want to thank my professors for providing the information to make my education possible. And finally, Dr. Alfred Traver who made this report a reality so that I could graduate on time. To all I say thanks.

ABSTRACT

Standards and Benchmark Tests

for Evaluating Large Scale Manipulators

with Construction Applications

by

Mark Edward Wiersma, M.S.E.

The University of Texas at Austin, 1995

COSUPERVISOR: Alfred E. Traver

COSUPERVISOR: Carl T. Haas

New applications of large scale manipulators for construction are continually emerging and making them multi-functional construction machines. This report presents a set of meaningful benchmark tests to gauge the overall static and dynamic performance of different large scale manipulators in order to achieve a means of relative comparison. The most important static and dynamic performance criteria are defined and a method provided for evaluating them.

The report reviews the application of human factors engineering to large scale manipulator acquired by The University of Texas. Furthermore, a method is presented to quantify potential improvements to the human-machine interface.

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CHAPTER ONE

INTRODUCTION

1.1 Background

The construction industry is ready for the introduction of autonomous technology. In particular, large scale manipulators, for instance automated back hoes and rebar placement machines, have shown great promise in improving safety, productivity, quality of construction and environmental impact (Hsieh and Haas 1993). The Construction Automation Group at the University of Texas focuses on the development of such systems.

1.1.1 Grove Pipe Manipulator

The large scale manipulator, hereafter referred to as the Manipulator, owned by the University of Texas at Austin, was originally designed by DuPont as a crane attachment for the purpose of installing large bore piping. The designs were submitted to the Grove Manufacturing Company for construction and the "Pipe Manipulator" became a reality in 1980. Glass (Glass 1984) presents a complete description of the crane mounted, electrohydraulically controlled device.

The initial expectations for the Manipulator were high. It was envisioned that the Manipulator would replace the smaller, but more versatile, "cherry picker"

(15-ton crane) in the erection of large piping systems like those found at large chemical processing plants. After its debut, however, the Manipulator proved to be slow, difficult to control and uneconomical to operate. As a result, workers regarded the Manipulator as inferior to the "cherry picker" and left it abandoned on the job-site. Supporters of the Manipulator were reluctant to give up on their new apparatus and thus invited the University of Texas to conduct a study to assess its merits and deficiencies. Figure 1.1 shows the Manipulator mounted on a 22 ton crane.

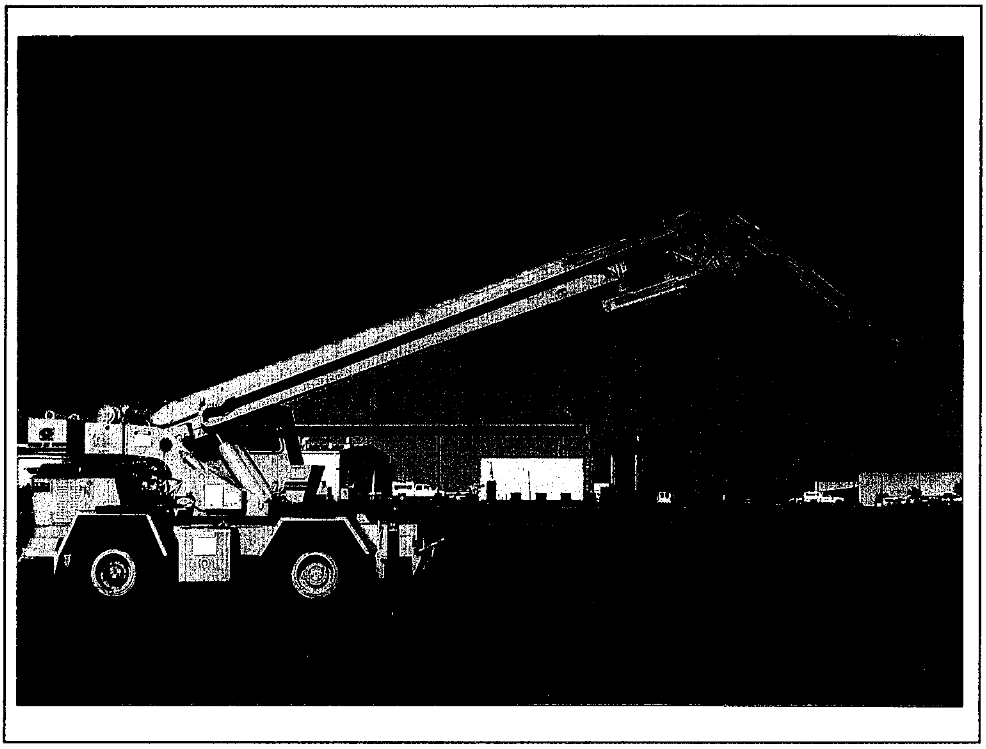


Figure 1.1 - Crane-Mounted Pipe Manipulator

1.1.2 Previous Manipulator Testing

Glass (Glass 1984) was the first to conduct a complete assessment to ascertain the Manipulator's strengths and weaknesses. Conducted on the construction site of a new chemical plant in southeast Texas, Glass's investigations determined that the Manipulator was plagued with numerous design flaws which hindered its mobility, speed and overall economic performance when compared to the capabilities of the "cherry picker". He further concluded that the control system was a primary contributing factor by reason of its number of control levers and their location, an operator basket fastened directly to the machine. Since the gravity leveling operator basket was mounted together with the Manipulator, slow arm movements were imperative for providing a safe ride for the operator. This suggests that the Manipulator was inherently slow for a reason. In addition, the eight control levers, necessary for controlling the Manipulator's eight degrees-of-freedom, often left the operator hesitating to determine proper maneuvering sequences to optimize performance. Amongst Glass's conclusions are the recommendations for removing the operator basket from the support frame and replacing the existing control levers with "joy-stick" controls. Future research and design would heed these recommendations.

Hughes (Hughes 1990) hypothesized "that the Manipulator will compete with a conventional crane in pipe spool erection cost, by use of a simple improved

teleoperator interface for arm control". Hughes' research culminated in the development of an entirely new man-machine interface with ergosticks serving as the controller. In designing a teleoperated controller, he also removed the controls from the operator basket allowing the operator to select his position anywhere within the range of a tether of control cables (approximately length 100 ft.).

To validate his hypothesis, Hughes contrived a test scheme fundamentally similar to the one used by Glass. Although the test was a simple pick-and-place scenario (Fisher 1989), it represented the first attempt at creating a benchmark to compare control schemes. Since his tests were performed in a laydown yard with inexperienced operators, Hughes compared his data to Glass' only after applying a "time productivity transformation equation" (Hughes 1990, pp. 120). This equation corrected:

1) The simplification of the pipe rack compared to the chemical plant configuration;
2) The inexperience of Hughes' volunteers;
3) The remote location of the control box removed from the operator basket.

In essence, Hughes used Glass' statistics as a benchmark to conclude whether his ergostick interface controller was an improvement over Groves' levers. He concluded it was not.

Thomas (Thomas 1995) continued to seek a more advanced controller that would increase the Manipulator's productivity. His research concluded with the purchase of a six degree-of-freedom optical force and torque sensor Dimension 6 Geometry Ball manufactured by CIS Graphics, Inc. The new controller was installed and tested for functionality. Up to this time no formal benchmark tests have been performed.

In addition to his controller research, Thomas moved the Manipulator into the controlled confines of the Construction Automation Lab. His design of a "cantilevered space frame" as a new Manipulator mount has made future development a more efficient and pleasant task. It is important to notice, however, that removing the Manipulator from the crane mount reduces the number of degrees-of-freedom from eight to six. Lab tests will be performed without the extendibility of the crane, thus reducing the scope of the overall analysis. Figure 1.2 shows the new Manipulator configuration.

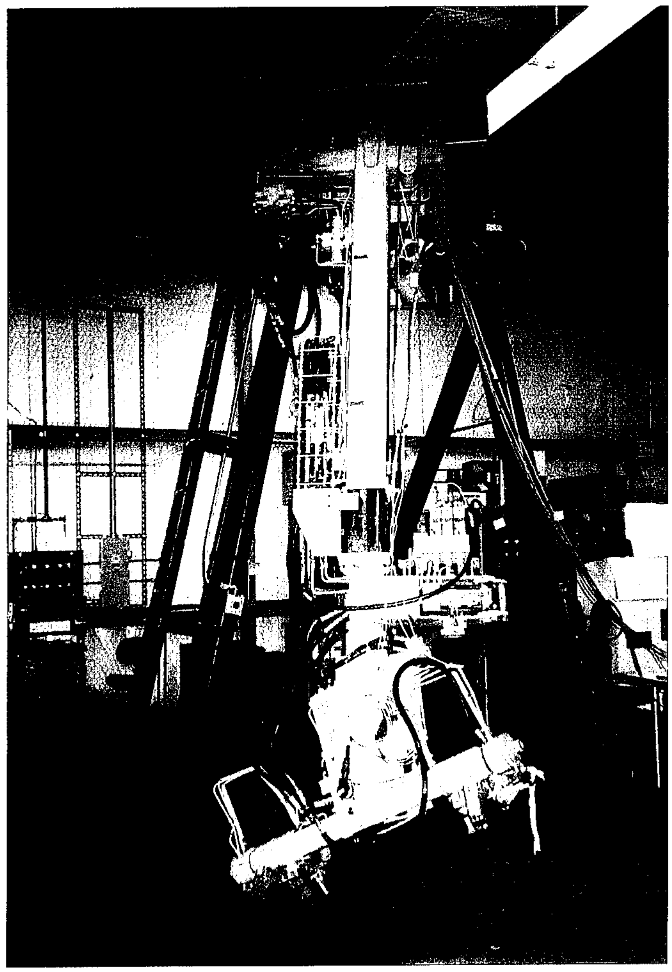


Figure 1.2 - Manipulator Mounted on Cantilevered Space Frame

1.2 Research Objectives

New applications of large scale manipulators for construction are continually emerging and making them multi-functional construction machines. The objective of this report is to provide a set of meaningful benchmark tests to

gauge the overall static and dynamic performance of different large scale manipulators in order to provide a means of relative comparison. The areas of performance measures, human factors, statistical analysis and benchmark tests for large scale manipulators are investigated.

1.2.1 Performance Measures

Today, a large variety of Manipulators are employed for many different uses ranging from the manufacturing assembly line to the construction site. Because such a vast assortment of Manipulators with diverse uses and shapes exists, standardizing specifications is difficult. However, there are certain qualifications which, all else being equal, permit Manipulators of similar type, size and function to be compared. This report reviews various methods of performance qualification for large scale manipulators for the purpose of ascertaining physical specifications.

1.2.2 Human Influence Analysis

A common paradox encountered in advancing control technology is the development of new systems that can potentially overwhelm their human operators. Since the human operator plays a vital role in the performance of the Manipulator, human factors cannot be over looked. System efficiency will remain

as dependent upon the capabilities of the operator as it does upon the capabilities of the Manipulator and its human-machine interface. The application of human factors engineering to the Manipulator is examined. In addition, a method to quantify potential improvements to the human-machine interface is presented.

1.2.3 Applying Statistical Analysis

This report examines the statistical methods for determining the probability that the Manipulator will achieve a desired target within a calculated standard deviation. The formulas for computing position accuracy, repeatability and there respective standard deviations are reviewed for both static and path-related output.

1.2.4 Benchmark Tests for the Large Scale Manipulator

This report will define the benchmark test procedures for evaluating the performance criteria of large scale manipulators. The performance tests presented in this report are based on the American National Standard for Point-to-Point (Static) Performance and for Path-Related (Dynamic) Performance evaluations for industrial robots and robot systems. The performance criteria are accuracy, repeatability, cycle time, overshoot, settling time, relative path accuracy, path repeatability, path speed characteristics and cornering overshoot. Methods of measuring the performance criteria are not discussed in this report.

CHAPTER TWO

PERFORMANCE MEASURES

This chapter reviews various methods of performance qualification for large scale construction Manipulators for the purpose of ascertaining physical specifications. There are several reasons for performance specifications:

- selecting a machine for a given task;
- planning work so that tasks fall within the capabilities of a given machine;
- setting goals for new equipment;
- generating benchmarks to gauge performance parameters of different machines, systems and techniques.

Today, a large variety of Manipulators are employed for many different uses ranging from the manufacturing assembly line to the construction site. Because such a vast assortment of Manipulators with diverse uses and shapes exists, standardizing specifications is difficult. However, there are certain qualifications which, all else being equal, permit Manipulators of similar type, size and function to be compared. The following sections define these qualifications.

2.1 Static vs. Dynamic Outputs

Output is the response of the Manipulator to input commands. Output is a specified movement or application of force to an object, and can be either static or dynamic in nature.

Static output results when the Manipulator approaches a target point and is held in a fixed position. Rebar and pipe placement are just two examples of static output. The important performance measure is the final position of the end-effector and its payload. In the absence of obstruction, the path followed by the end-effector in the performance of the task is irrelevant. Static outputs are much easier to measure since the outcome is not in motion.

Dynamic output, in contrast, results when the Manipulator follows a specified path. Evaluation of dynamic output is more difficult because it entails continuous measurement of the end-effector position during the execution phase. Tracking and surface following are two examples of dynamic outputs.

2.2 Accuracy

Accuracy is the measure of the difference between the desired output and the achieved output when there is no memory of previously performed tasks. The expected error of the output about the mean achieved output when added to the

mean accuracy represents some degree of confidence of the accuracy (Colson 1984).

There are two types of accuracy, absolute and relative. They differ only in their frames of reference. Absolute accuracy is measured relative to the Manipulator's base coordinate system. Figure 2.1 illustrates how absolute accuracy relates to the Manipulator's base coordinate system.

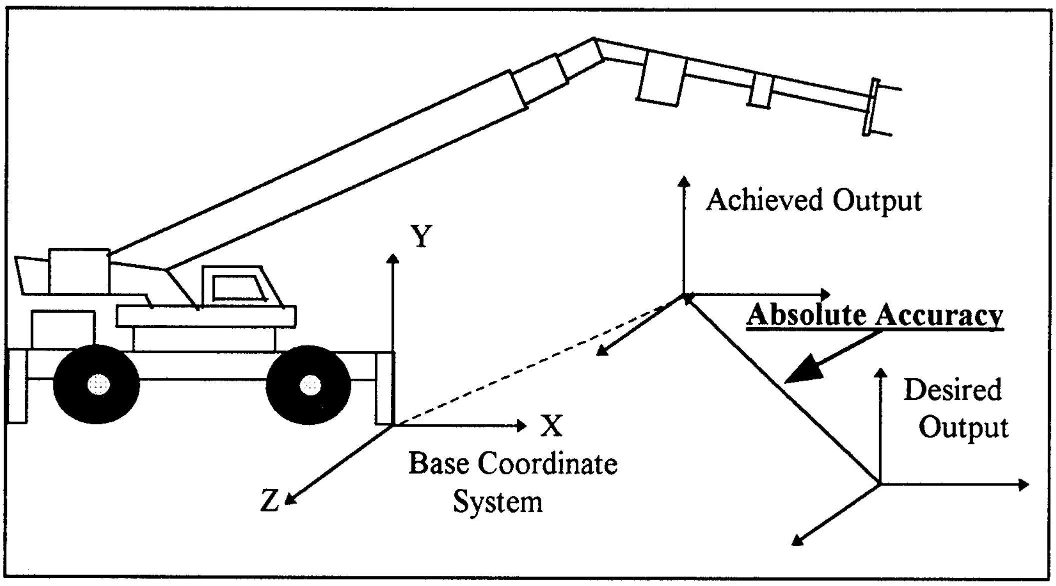


Figure 2.1 - Absolute Accuracy

Relative accuracy is measured from a previously achieved output. Relative accuracy occurs when a specified output is planned from some calibration point other than the base coordinate system. It is an especially important performance measure when working with tool jigs or when working from a benchmark on a

construction site. It is assumed that the relative accuracy of the Manipulator is adequate enough so that given a calibration point other than the base coordinate system, subsequent output can be determined with some level of confidence. Relative accuracy is the measure of accuracy of location points within the Manipulator's work space to a calibration point located within the work space. Figure 2.2 illustrates the concept of relative accuracy.

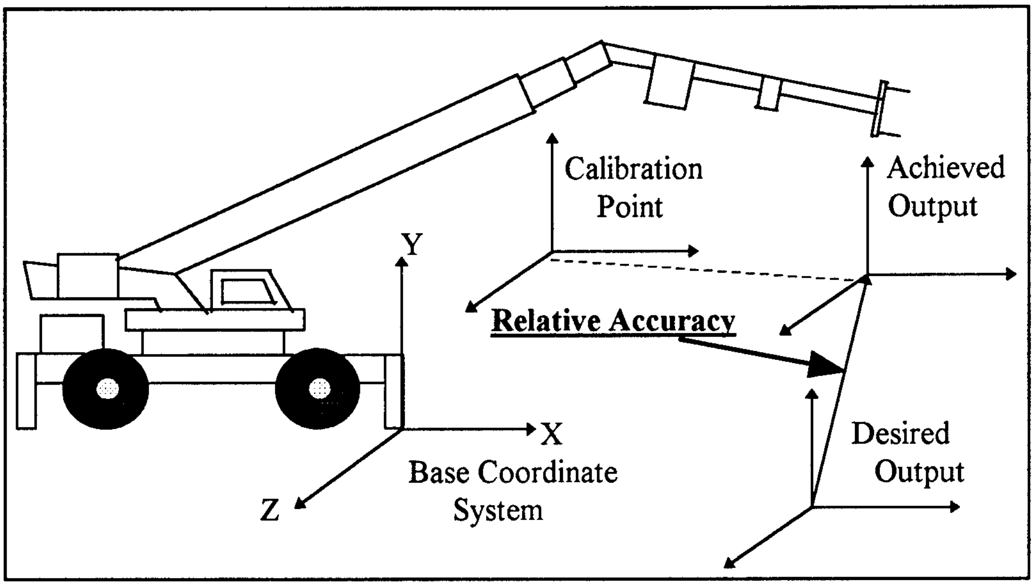


Figure 2.2 - Relative Accuracy

2.3 Repeatability

Repeatability is the measure of how closely the achieved output clusters about its mean. Todd (Todd 1986) illustrates the difference between repeatability and accuracy in the Figure 2.3.

In the target analogy of Figure 2.3, each dot represents an attempt to achieve the desired output, in this case, hitting the cross-hairs on the target. The size of the dot cluster represents the measure of repeatability and the closeness of the center of the cluster represents the accuracy. It is clear from this figure that it is possible to obtain a high level of repeatability without being accurate. It is important to note the difference between accuracy and repeatability.

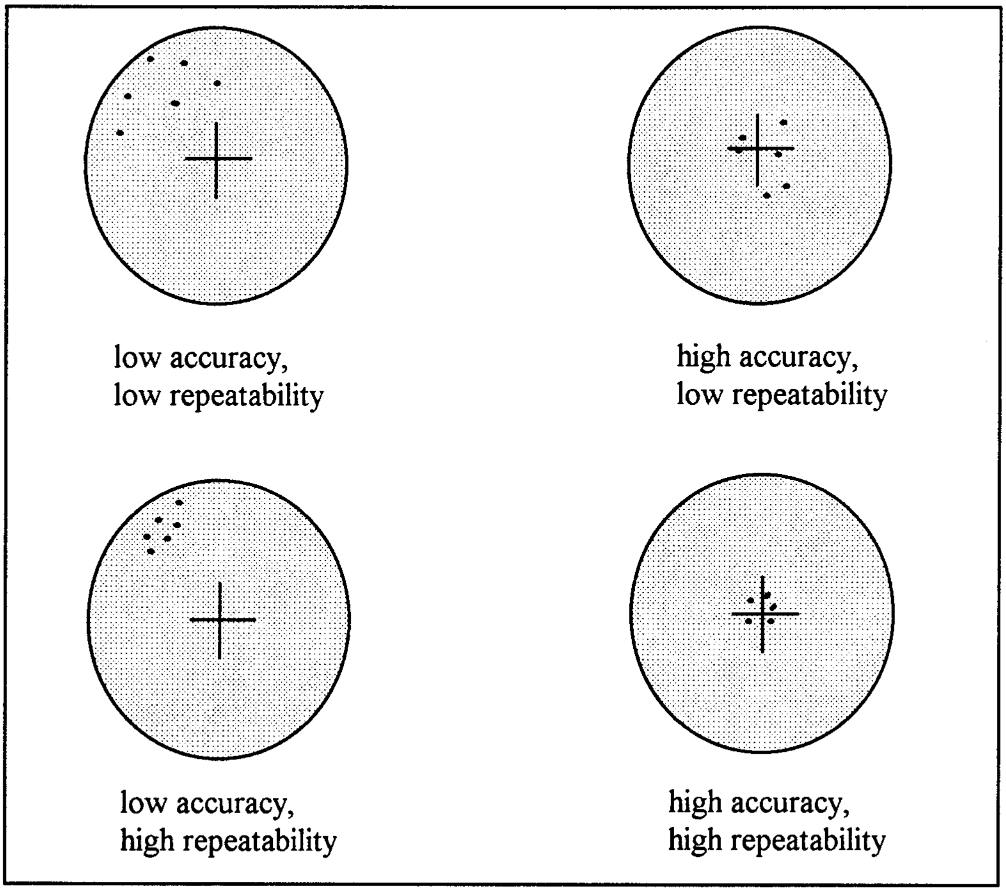


Figure 2.3 - Accuracy vs. Repeatability (Todd 1986)

Repeatability is a very powerful benefit to an autonomous Manipulator. It denotes the ability to repeat programmed outputs consistently. Repeatability is more valuable than accuracy; if the error is constant, accuracy can always be corrected. For these reasons, repeatability is often considered more meaningful performance measure than accuracy.

2.4 Resolution

The capability of feedback devices (encoders) in coordination with the control system in determining the locality of the end-effector and its calibration point determines the resolution of the Manipulator. In broader terms, Wodinski (Wodinski 1987) defines resolution as the measure of the smallest possible increment of change in the variable output of a device or position sensors.

Although resolution is ultimately determined by the capabilities of the system's actuators and components, to the user it is simply the minimum consistently commandable output that is measurable at the end-effector. Resolution comprises both position and orientation of the Manipulator's end-effector.

Resolution has some degree of impact on the teach-and-repeat capabilities of the Manipulator, such as teaching the Manipulator to place a cylindrical bar into a round hole. If the tolerance of the bar and hole fit is smaller than the resolution

of the Manipulator system, then insertion of the bar into the hole may never be possible. Fortunately there are many construction applications for which high tolerance specifications are not required.

2.5 Celerity

There are two primary performance criteria associated with the speed of the Manipulator. One is economic and the other kinematic. Performance specifications provided by the manufacturer almost always include speed. The engineer embarked on the advancement of the Manipulator's capabilities must often evaluate the machine's swiftness and speed in economic terms. Engelberger (Engelberger, 1980), a pioneer in robotics research, writes "no matter what the social benefits are, no matter how clever the technology, no matter how pretty the robot is to watch, every proposed investment in robotics has to pass the test of critical financial appraisal." Perhaps financial performance is the toughest test of all. The most brilliant innovations are failures if they lose money or even if they cannot provide an attractive return for the investor. In theory, at least all money is competing for the highest possible return.

Glass (Glass 1984) measured the performance of the prototype Grove "Pipe Manipulator" by comparing its operating cost efficiency to that of the incumbent "cherry picker." Unfortunately for Grove and DuPont, the "cherry

picker" was the better performer and the Manipulator was taken off the jobsite and given to the University for further research and development.

Hughes (Hughes 1989), after devising a new control scheme, proceeded with the same economic analysis methods. He knew that replication of the original test procedure was essential for comparison and ultimately to validate his hypothesis.

In order to properly evaluate the Manipulator's improved control characteristics, it is essential to relate new benchmark tests to the previously used economic ones. This is the only way to quantify performance improvements. Hughes accomplished this by applying a "productivity transformation equation" to his results to enable a comparison of the present and past. Likewise, such transformations offer the opportunity to arrive at the wrong conclusion if not done carefully.

From a kinematic standpoint, both velocity and acceleration will have important impacts upon the rate of performance of the Manipulator. Because cycle time is of substantial concern for the applications engineer, benchmarks for the maximum speed of each degree-of-freedom will be important. Appleton and Williams (Appleton and Williams 1987) suggest the following:

> One approach that is useful for comparison purposes is to define a test cycle and measure the total travel time. The test cycle should be repeated a number of times and a mean and standard deviation determined for the cycle time. Within a simple trajectory it might also be useful to

know the speed variation, the mean speed and the average speed, all of which are useful for building up theoretically predicted cycle times.

Maximum and minimum accelerations will be important for end-effector design. This information is necessary for determining the forces required to hold items securely to avoid slippage during handling operations.

Finally, it is important to bear in mind that the speed of the Manipulator during unconstrained point to point movement will be faster than during continuous path control movements necessary during tracking and surface following. The control of speed and the control of position are intimately related for path following applications.

2.6 Overshoot and Settling Time

In robotics ANSI defines overshoot as the "largest distance of overtravel past the target position along the direction of motion after the robot is within a settling bandwidth ($\pm S$)." S is the standard deviation and is defined later. Overshoot is predominate during "violent changes in direction and mass and during acceleration and deceleration." (Warnecke et al. 1985) Cornering overshoot is defined by ANSI as the largest deviation outside of the reference path after the Manipulator has passed" the corner.

Settling time is "a period of time required for the robot to remain within a limit (±*S*) from the target point after a move command is executed. Sometimes settling time is called oscillation. Settling time is measured as the elapsed time starting from initial crossing into the limit band to the last point that is outside this limit." Overshoot and settling time are shown in Figure 2.4.

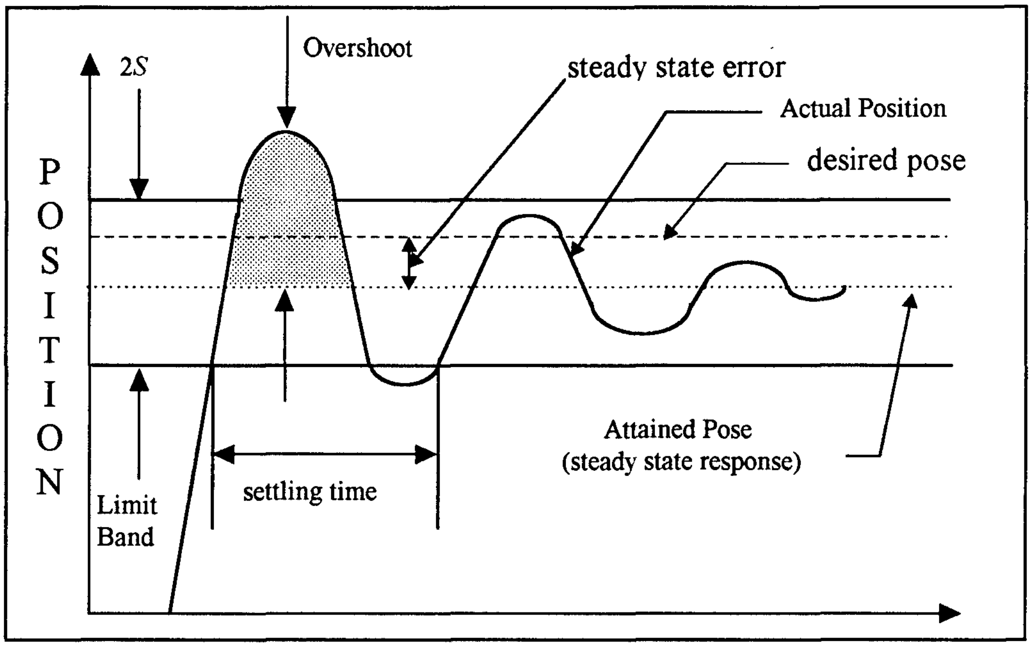


Figure 2.4 - Overshoot and Settling Time (ANSI/RIA R15.05-1 90)

Overshoot should be measured to quantify the Manipulator's capability to make smooth and accurate stops at target points. This is an important performance measure during applications involving large inertias, high speeds or frequent stops. Settling time should be measured to quantify how quickly the

Manipulator can stop at a target point. Overshoot and settling time are related parameters. Note both overshoot and settling time depend not only on the mass distribution of the Manipulator but also on the mass distribution of the payload.

ANSI/RIA 15.01-1 90 outlines the American National Standards for measuring overshoot and settling for industrial robots and robot systems. ANSI/RIA 15.01-2 92 outlines the standards for measuring cornering overshoot.

2.7 Compliance

Static compliance is the amount of elastic deflection of the Manipulator under a static force. ANSI/RIA 15.01-1 90 outlines a method for measuring the three principal compliance components along a robot's base coordinate system. Both torsional compliance and coupling effects are excluded.

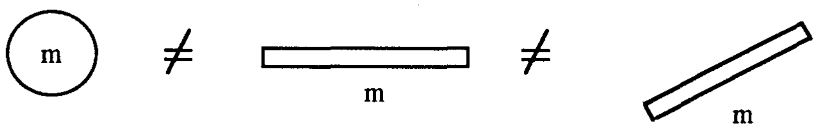
Dynamic values (frequency, damping, amplitude, phase) are also important design criteria. Here modal analysis is a useful tool for Manipulator design.

2.8 Sensitivity

Specific sensitivities important to the Manipulator are payload, direction of approach, temperature and geometry properties. All of these factors influence the accuracy, repeatability and resolution of the Manipulator system.

2.8.1 Payload

Payload refers to the item handled alone and does not include the end-effector or arm, which is considered part on the Manipulator. If the arm has multiple end-effector attachments, each attachment should be benchmarked separately because of weight and functionality differences. The effect of payload is complicated by the fact that it depends not only on the mass of the payload but also on the mass distribution and orientation.



The inertia of the Manipulator-payload system will have substantial impact upon overshoot and oscillation. System inertia is dependent upon the instantaneous payload position or the load and end-effector position at anytime given instant. System damping is critical to attaining targets with minimal overshoot and settling time.

Since loading affects speed, accuracy and resolution, various loading conditions must be benchmarked. Appleton and Williams (Appleton and Williams 1987) recommend testing at 0, 50 and 100% of maximum payload and at 20, 50, or 100% of speed available.

2.8.2 Direction of Approach

One of the hindering design points discovered by Glass (Glass 1984) on the original Grove "Pipe Manipulator" was limiting movement parameters. He observed that the pivoting, booming, and telescoping characteristics of the Manipulator limited its productivity and usefulness. These conditions made the Manipulator very sensitive to the direction of approach chosen by the operator.

Consider putting a round peg in a round hole as illustrated in figure 2.4. This figure clearly demonstrates the sensitivity associated with direction of approach of a kind encountered in autonomous Manipulators.

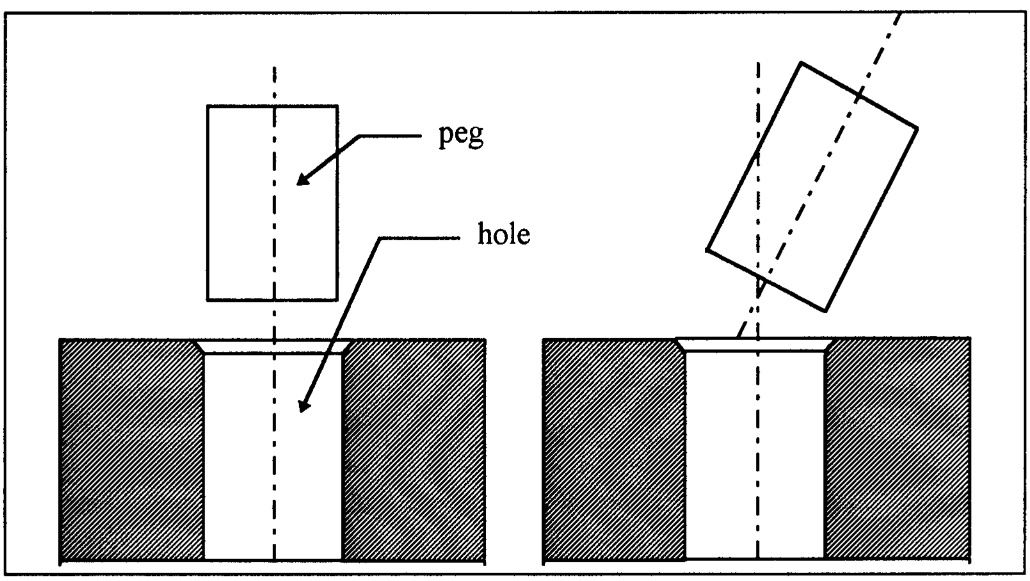


Figure 2.5 - Peg in a Hole Problem (Appleton and Williams 1987)

2.8.3 Temperature

Hydraulic systems, especially those used in heavy equipment, suffer from the influence of heat. In hydraulic equipment such as the Manipulator, oil is pressurized and released as it circulates through the system. Heat is generated and the oil temperature rises. Some of this heat is gradually transferred to the structure and joints and serves to raise the temperature of the machine components.

Gradual heat build up affects the feedback system, causing overall positional drift. Procedures should be implemented to reach a stable operating temperature quickly and remain there. Sufficient time must be allowed for warm up before testing commences. Care should be taken to maintain temperatures during stoppages.

2.8.4 Geometry Properties

Figure 2.5 illustrates that geometry sensitivity often plays a role in accentuating or attenuating position errors. Revolute joints such as the one depicted in the Figure 2.5 tend to be greater sources of errors than prismatic joints.

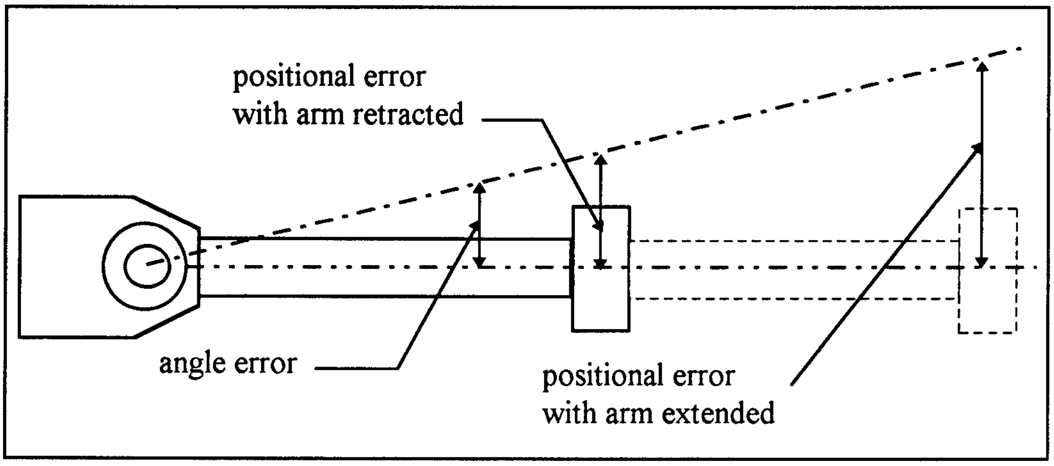


Figure 2.6 - Sensitivity of Extended Arm (Todd 1986)

CHAPTER THREE

HUMAN INFLUENCE ANALYSIS

3.1 Human Factors Engineering

Human factors engineering is the study of new technological products and the people who make them work. Adams (Adams 1989) provides a more formal definition:

> The field of human factors engineering uses scientific knowledge about human behavior in specifying the design and use of a human-machine system. The aim is to improve system efficiency by minimizing human error.

The United States government played a key role in the evolution of human factors research. During World War II, engineering systems became increasingly complex and compelled the government to establish new test centers at Wright-Patterson and Brooks Air Force Bases. More recently, human factors engineering, referred to by some as ergonomics, has become even more important with more and more utilization of state-of-the-art microprocessor control technology.

Today's technological advancements continue to expand the performance envelope of machines and machine systems at an unprecedented rate. Unfortunately, these advancements come with a rather hefty price tag. Moreover,

accompanying these high tech and high cost components is the disadvantage of complexity. This is important to note since "the need for human factors engineering grows in direct relationship to complexity of the man-machine systems." (Olex et al. 1983).

A common paradox encountered in advancing technologies is the development of new systems that can be exceptionally difficult to use and even overwhelm their human operators. Since the human operator plays a vital role in the performance of the Manipulator, human factors cannot be over looked. System efficiency will remain as dependent upon the capabilities of the operator as it does upon the capabilities of the Manipulator and its control system.

Human factors engineering also considers the social and motivational issues in the analysis, design, implementation, control and operation of the Manipulator. However, these topics are beyond the scope of this report. The reader is referred to Graham (Graham 1991), Adams (Adams 1989) or Sanders (Sanders et al. 1993) for further information.

3.2 Human Factors and the Manipulator

Glass (Glass 1984) observed that the Manipulator's eight control levers, necessary for controlling the Manipulator's eight degrees-of-freedom, often left the operator hesitating to determine proper maneuvering sequences to optimize

performance. Consequently, Dupont had a pipe manipulating machine that was very difficult to control efficiently. But, more importantly, when compared to the less expensive “cherry picker”, the “Pipe Manipulator” was found too uneconomical to operate. Both had similar operating costs but the duty cycle of the “Pipe Manipulator” was too low and required a large active site to stay busy. When not busy moving pipe, the retention of the crane function would have increased the “Pipe Manipulator’s” flexibility and usefulness. Although Glass observed other design factors that hindered performance of the prototype machine, control has been a primary focus for the University of Texas Construction Automation Lab.

Hughes (Hughes 1990) chose the man-machine interface as his topic of research since better control would correct “intolerably slow and clumsy operation." He envisioned the Manipulator as a tool to be used by a craftsworker without any particular heavy equipment training. He also believed that new controls would provide a path for continued advancement to higher levels of automation.

The possibility always exists, however, of designing an autonomous Manipulator too complex for the average user to efficiently operate. This, of course, defeats the purpose of creating a better, more powerful control system. Recent undertakings to improve the Manipulator control system include Hughes’

(Hughes 1990) "ergosticks" and more recently, Thomas' (Thomas 1995) Dimension 6 Geometry Ball. These efforts have focused on teleoperated control, were the human operator guides the Manipulator through a joystick or similar device. Clearly the human operator remains an integral part of the control loop.

There are a number of human issues that need investigating in order to improve the human-Manipulator interface. These include, but are not limited to, the following:

- safety (always the first priority),
- perceptual limitations of the human operator including visibility and dexterity,
- operator training,
- software interface design,
- robustness of design,
- discriminability of controls and control axes.

The anticipated outcome of applying human factors engineering is simple. When applied effectively it should increase the compatibility of the human operator with the Manipulator control system. This approach does not increase the overall capability of the system, but makes it more user friendly. The end result is a machine easier to operate for the human user. Perhaps then the "cherry picker"

will become the obsolete piece of construction equipment Glass (Glass 1984) predicted.

3.3 Human Factors Tests of the Manipulator

Hughes (Hughes 1990) performed a series of simple tests to validate his hypothesis that the Manipulator will compete with a "cherry picker" in pipe erection cost. In these tests, a set of operators erected pipe using the Manipulator in a simulated plant environment. The experimental variable was task completion time. His "ergosticks" open loop rate interface time was the test variable and the Grove interface time was the control. Other measurements consisted of all operator inputs and Manipulator main boom positions versus time.

The tests performed were simple but effective. Four inch plastic pipe was picked up from a lay down area at ground level and placed on an elevated pipe rack. Figure 3.1 illustrates the test layout.

During the execution of these tests, Hughes made some interesting discoveries about the human factors associated with his new controller. He explains in detail the problems associated with operator vision during teleoperation. Among his findings was that translational and angular alignment of the Manipulator jaws from a remote command site had certain affixed human limitations. Accurate pick and placement of the pipe was dependent upon the

operator's depth perception at a distance of 40 feet.

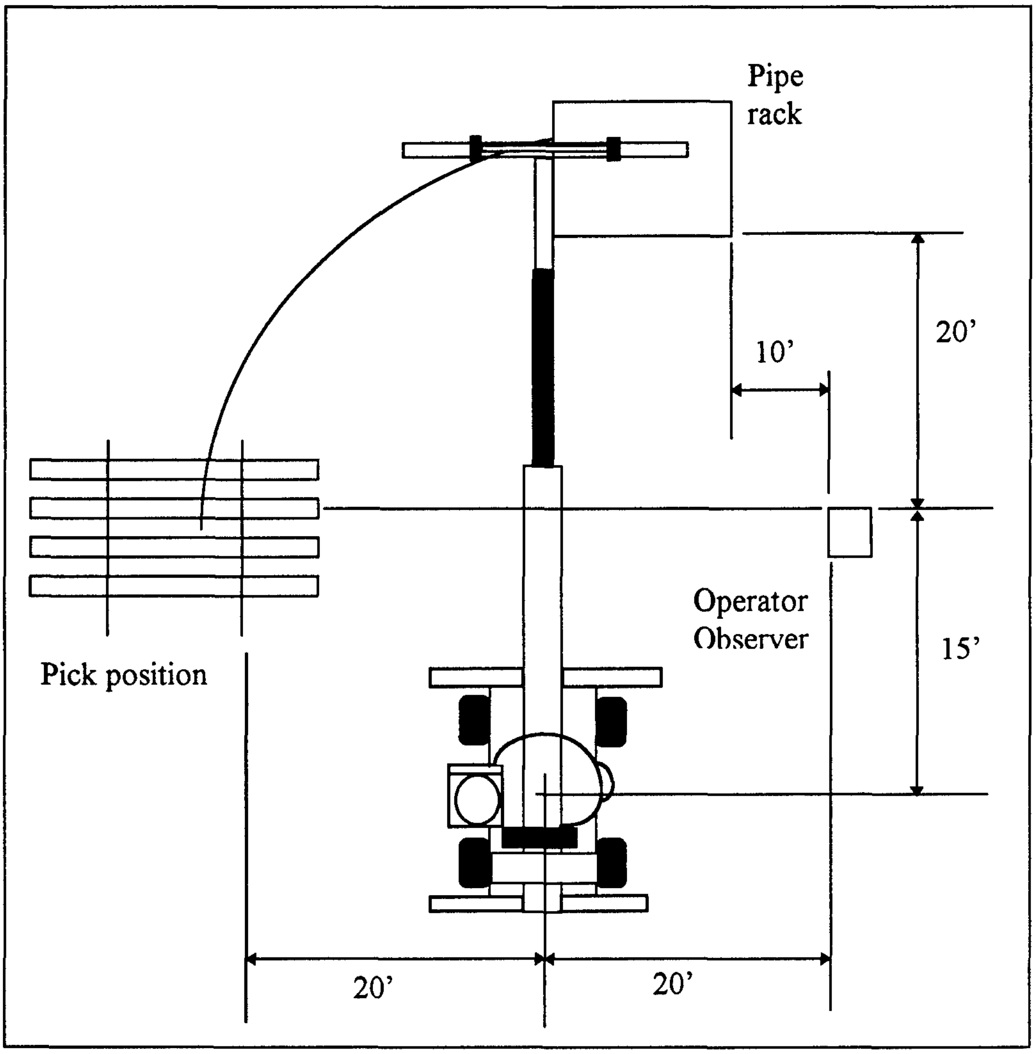


Figure 3.1 - Hughes' Validation Test Arrangement

In addition, general observances regarding the "ergosticks" from the test operators summarized repeated confusion between control axes, neutral positions were not firm enough and control arms were uncomfortable/wrong height. In contrast, the Grove controls seemed complicated and difficult to distinguish during lifting operations. He concluded that close attention must be paid to the location of the controls and the tasks of the Manipulator operator. It is not surprising that these observations are associated with human factors.

Testing is important for validating and quantifying any design improvement. Hughes' tests were simple to set up and run, and represented a typical task regularly performed on construction sites.

3.4 The Learning Curve

Nof (Nof, 1985) describes learning "as the process by which the time or the cost per cycle decreases as the number of performed, repetitive cycles increases." The learning process has been observed in humans to follow the typical learning curve given by the equation:

$$T(n) = T(1) \times n^{-A}$$

where: T = time (or cost) per cycle
T(1) = time (or cost) of the first cycle
n = the number of cycles performed
A = an improvement constant, determined by the learning rate.

Figure 3.2 shows a typical learning curve.

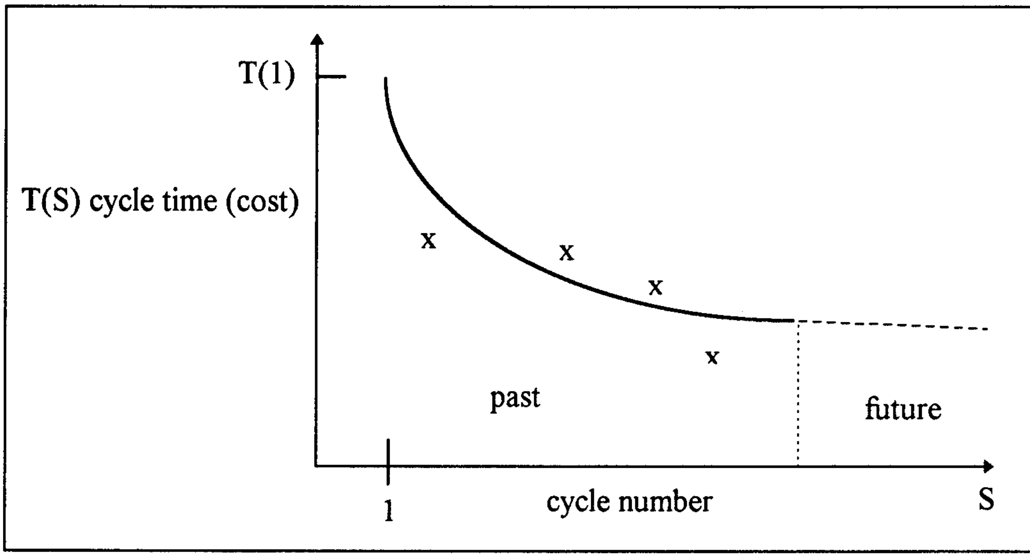


Figure 3.2 - The Learning Curve (Nof 1985)

The main factors in human learning are (Nof 1985):

1. person's age;
2. the amount of previous experience in learning;
3. personal physical and psychological capabilities;
4. the job complexity in terms of cycle length, amount of uncertainty, and degree of similarity to previous jobs.

Now we can describe mathematically the learning curve associated with each new control system tested.

Hughes' recorded the average erection time versus the first, second and third pipe spool erected for each interface configuration (Grove and "ergosticks").

Hughes' Test Results		
Erection time (sec)	Pipe Spool Number	
245	1	"Ergosticks"
240	2	"Ergosticks"
202	3	"Ergosticks"
300	1	Grove
215	2	Grove
225	3	Grove

The graph is shown in Figure 3.3.

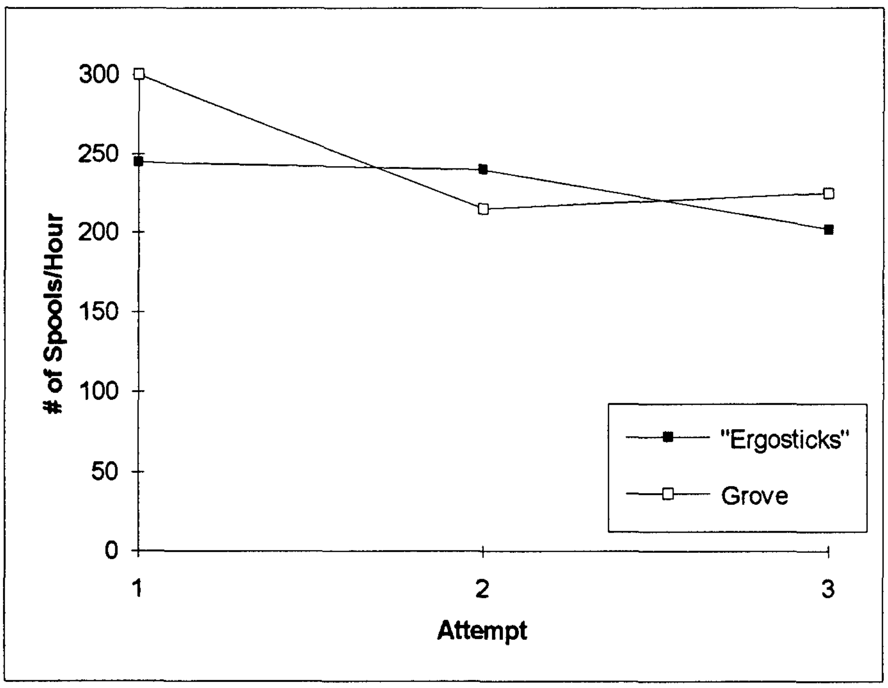


Figure 3.3 - Learning Curve for Hughes' Pipe Spool Erection Test

Note that smoother curves can be attained by obtaining more data and curve fitting the results as shown in Figure 3.1. It is clear from this graph that both curves are nearly flat. This is an indicator of the difficulty in operating each system.

By performing the identical test on new control systems, we can directly compare the curves (old versus new) and quantify, both numerically and graphically, the improvement associated with each new control system. The "steepness" of the learning curve will be the indicator of the operator's ability to learn the system. The "steeper" the curve the quicker it is to learn.

CHAPTER FOUR

APPLYING STATISTICAL ANALYSIS

Statistics is a science for analyzing data to ascertain errors, precision, and general validity of experimental measurements. One of the major branches of statistics is probability. Probability provides tools and methods for describing random variations in a system.

This chapter will examine the statistical methods for determining the probability that the Manipulator will achieve a desired target within a calculated standard deviation. The formulas for computing position accuracy, repeatability and their respective standard deviations will be reviewed for both static and path-related output. But first, we shall briefly review the various sources of error that hinder performance.

4.1 Error Types

Inherent in the Manipulator are various sources of error that adversely affect its accuracy and repeatability performance. Improving the Manipulator's performance will require understanding these sources. The factors that influence performance are categorized as geometric, nongeometric, or dynamic in nature (Hudgens and Tesar, 1992). A brief description of each is given below:

- Geometric factors are essentially state independent constants that define the static input/output relationship between desired output coordinates and Manipulator achieved coordinates. These error sources include: kinematic parameter error, Manipulator placement error, encoder resolution, gear error, etc.

- Nongeometric factors are dependent upon load and environmental conditions and affect the kinematic input/output connection of the system. These errors include: compliance, gravity, backlash, temperature, etc.

- Dynamic factors affect the higher order performance of the Manipulator and are also state dependent. These errors include: inertia, friction, vibration, control system dynamics, etc.

Together these sources of error make it impossible for the Manipulator to achieve desired outputs exactly.

The robotics community employs several performance enhancement solution techniques to improve industrial robot performance. These techniques

are categorized as (1) design, (2) sensing, or (3) control (Hudgen and Tesar, 1992). Design solutions are based on improvements in robot construction such as employing higher manufacturing tolerances or designing lighter and stiffer components. This is perhaps a long term solution for future Manipulators but not applicable to our current version. Sensor enhancement solutions use an external sensing system to eliminate error by adjusting joint feedback signals. This is very expensive and not practical for the Manipulator. Finally, the control enhancement solutions typically implement standard independent-axis PID (*Proportional Integral Derivative*) control strategies. Although this solution is more economical, the level of sophistication might prohibit its use on the Manipulator.

Whether the Manipulator will need a performance enhancement boost will depend upon the statistical data collected from performance testing The next section describes the statistical analysis presented in ANSI/RIA 15.05-2 90 and 92.

4.2 Statistical Formulas

The following statistical formulas have been defined by ANSI to quantify the static and path performance criteria of Robots. This report will apply the same performance criteria to the Manipulator.

Position accuracy is a statistical measure of the spatial deviation between commanded and achieved Manipulator positions. It is the measured difference between the commanded pose and the attained pose of the Manipulator. Here pose is defined as a position and orientation in space. The magnitude of the accuracy deviation (d_i) at the ith position is given by:

$$d_i = \sqrt{\left(X_{ai} - X_{ci}\right)^2 + \left(Y_{ai} - Y_{ci}\right)^2 + \left(Z_{ai} - Z_{ci}\right)^2},$$

where X_{ai}, Y_{ai} and Z_{ai} are the coordinates of the attained pose at the ith measurement and X_{ci}, Y_{ci} and Z_{ci} are the corresponding commanded pose coordinates.

4.2.1 Static Accuracy

The two statistical measures for static accuracy are mean and standard deviation. The mean position accuracy ($\overline{d}_{pa}$) is given by:

$$\overline{d}_{pa} = \frac{1}{N}\sum_{i=1}^{N} d_i .$$

And its standard deviation (S_{PA})is:

$$S_{PA} = \sqrt{\frac{\sum_{i=1}^{N}(d_i - \bar{d}_{pa})^2}{N-1}}$$

where N is the total number of measurements. For engineering experiments, Holman (Holman 1984) maintains that it is desirable to use at least 20 measurements in order to obtain reliable estimates. ANSI suggests at least 50 measurements for testing robotic systems.

4.2.2 Path Accuracy

ANSI defines path accuracy as the measurement of the distance between a reference path and any given attained path. Two types of path accuracy, relative and absolute, are presented in ANSI/RIA 15.05-2 92. They differ only in the definition of the reference path used to compute deviations. However, ANSI recommends using the relative path type because this approach simplifies the necessary measurement methods. Nevertheless, the following formulas apply regardless of which type is used. The relative path accuracy test, and all other tests, will be outlined in chapter five.

The two statistical measures for path accuracy are maximum and average deviation. ANSI defines maximum deviation (AC) as the maximum distance between any given path and the corresponding reference path. The magnitude of the maximum deviation of the worst path (AC_{REL}) is given by:

$$AC_{REL} = \max_{i=1}^{n} \max_{j=1}^{n} \sqrt{(U_{a_{ij}} - U_{r_{ij}})^2 + (V_{a_{ij}} - V_{r_{ij}})^2},$$

where n is the number of measurement cycles (minimum of 10), $(U_{a_{ij}}, V_{a_{ij}})$ are the coordinates of the attained path and $(U_{r_{ij}}, V_{r_{ij}})$ the coordinates of the reference path for the *i*th cycle and *j*th evaluation point. See Figure 4.1.

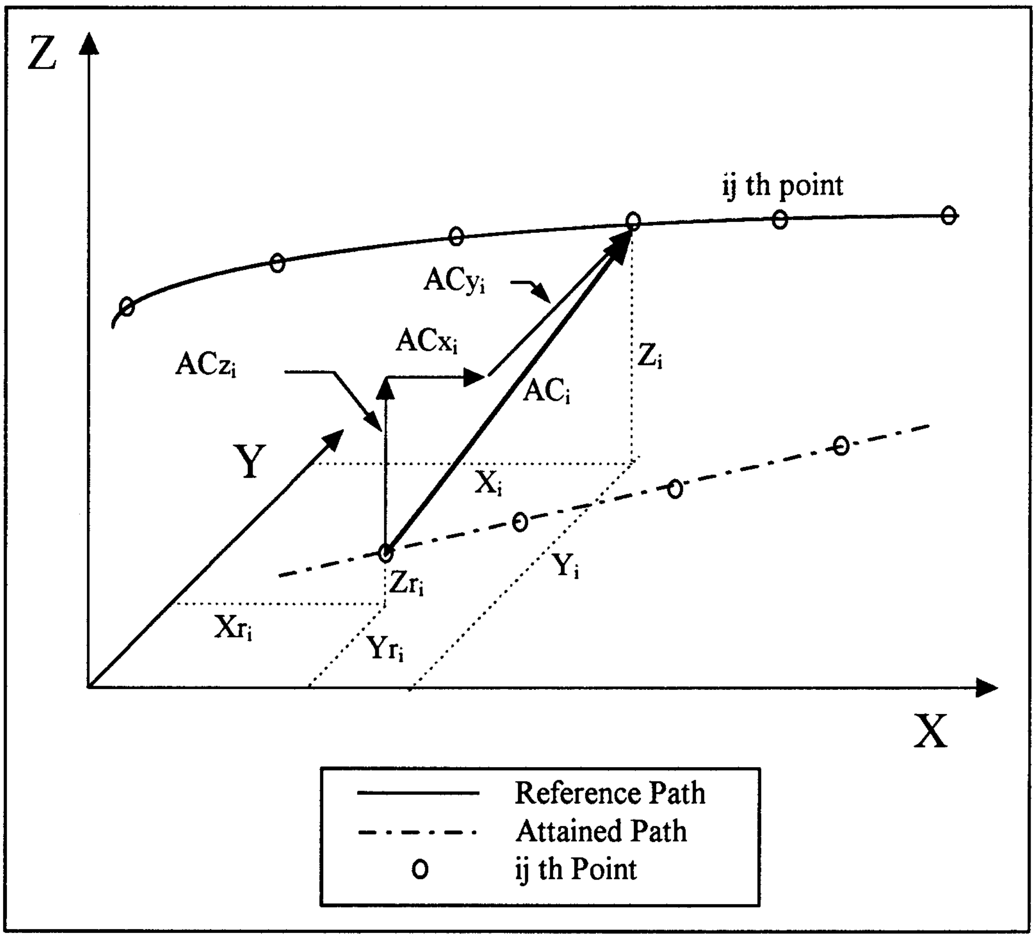


Figure 4.1 - Path Accuracy Definition (ANSI/RIA R15.05-2 92)

The average deviation is the average of the distances between any given attained path and the corresponding reference path. The magnitude of the average relative path accuracy ($\overline{AC}_{REL}$) is calculated as follows:

$$\overline{AC}_{REL} = \frac{1}{m}\sum_{j=1}^{m}\sqrt{(\overline{U}_{a_j} - U_{r_j})^2 + (\overline{V}_{a_j} - V_{r_j})^2},$$

where $(\overline{U}_{a_{ij}}, \overline{V}_{a_{ij}})$ are the coordinates defined by:

$$\overline{U}_{a_j} = \frac{1}{n}\sum_{i=1}^{n} U_{a_{ij}} \text{ and}$$

$$\overline{V}_{a_j} = \frac{1}{n}\sum_{i=1}^{n} V_{a_{ij}} \ .$$

4.2.3 Static Repeatability

ANSI defines static repeatability as the measure of deviations between achieved output and the mean of the output after commanding the Manipulator to the same pose n times from the same direction. This test will measure the Manipulator's unidirectional repeatability. Omnidirectional repeatability is the measure of repeatability when the Manipulator approaches from different directions.

Three measurement locations are used in the test and the arithmetic mean must be calculated at all three locations before calculating the mean and standard deviation of repeatability. The mean is given by:

$$\overline{X}_{(a,b,c)} = \sum_{i=1}^{n} \overline{X}_{(a,b,c)_i}$$

$$\overline{Y}_{(a,b,c)} = \sum_{i=1}^{n} \overline{Y}_{(a,b,c)_i}$$

$$\overline{Z}_{(a,b,c)} = \sum_{i=1}^{n} \overline{Z}_{(a,b,c)_i}$$

Where $(a,b,c)_i$ are the three measurement locations for the *i*th cycle for a total of n cycles. ANSI suggests completing five hundred cycles after system stabilization has occurred. Seventy-five to one hundred cycles would be more appropriate for the Manipulator.

The deviation (*d*) for each measurement is determined by the equation:

$$d_{(a,b,c)_i} = \sqrt{(X_{(a,b,c)_i} - \overline{X}_{(a,b,c)})^2 + (Y_{(a,b,c)_i} - \overline{Y}_{(a,b,c)})^2 + (Z_{(a,b,c)_i} - \overline{Z}_{(a,b,c)})^2}\ .$$

Thus, the total mean repeatability ($\overline{d}_{REP}$) is:

$$\overline{d}_{REP} = \frac{\sum_{i=1}^{n} d_{ai} + \sum_{i=1}^{n} d_{bi} + \sum_{i=1}^{n} d_{ci}}{3n}\ ,$$

Now, the standard deviation (S_{REP}) can be computed from:

$$S_{REP} = \sqrt{\frac{\sum_{i=1}^{n}(d_{ai} - \overline{d}_{REP})^2 + \sum_{i=1}^{n}(d_{bi} - \overline{d}_{REP})^2 + \sum_{i=1}^{n}(d_{ci} - \overline{d}_{REP})^2}{3n - 1}}\ .$$

4.2.4 Path Repeatability

ANSI defines path repeatability as the measure of the closeness between multiple paths. The statistical data calculated for path repeatability is same as relative path accuracy except that dynamic path repeatability uses a reference path that is the average of a path traversed n times. ANSI recommends completing a minimum of ten (n = 10) path cycles.

Path repeatability is a scalar value that represents the magnitude of the deviations in a given evaluation plane (defined in Section 5.2.7). These deviations are measured in the coordinate system of the evaluation plane (see Figure 4.2). The path deviation (D_{ij}) is given by:

$$D_{ij} = \sqrt{(U_{a_{ij}} - \overline{U}_{a_j})^2 + (V_{a_{ij}} - \overline{V}_{a_j})^2}$$

The maximum path repeatability (PR) is:

$$PR = \max_{j=1}^{m} \max_{i=1}^{n} D_{ij} .$$

And the average path repeatability ($\overline{PR}$) is:

$$\overline{PR} = \max_{j=1}^{m} \frac{1}{n} \sum_{i=1}^{n} D_{ij} .$$

Again, m is the number of evaluation points (j), n is the number of measured cycles (I) and $(\overline{U}_{a_j}, \overline{V}_{a_j})$ are the coordinates defined by:

$$\overline{U}_{a_j} = \frac{1}{n}\sum_{i=1}^{n} U_{a_{ij}} \text{ and}$$

$$\overline{V}_{a_j} = \frac{1}{n}\sum_{i=1}^{n} V_{a_{ij}} .$$

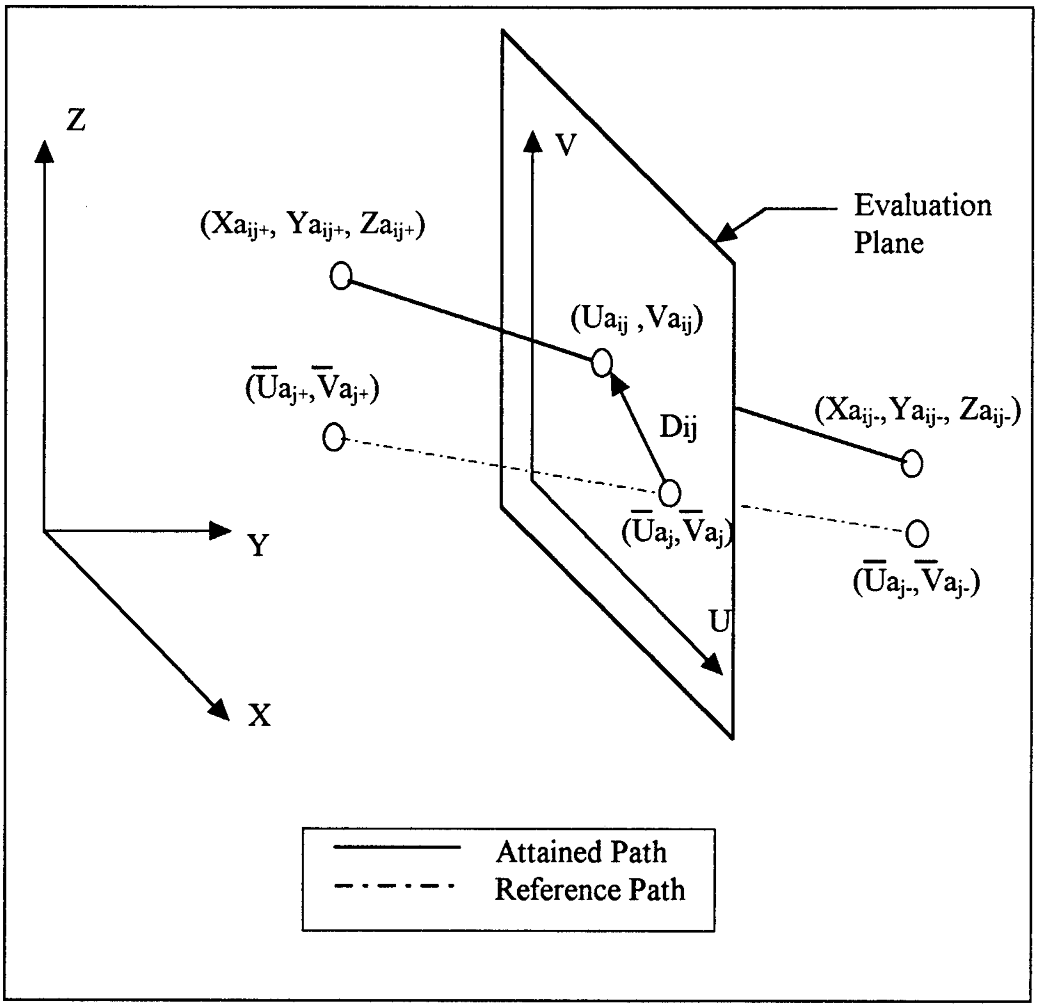


Figure 4.2 - Projection of Attained Path onto Evaluation Plane

4.3 Probability Distribution

Repeatability is necessary for reliable replication of motion sequences that are taught on-line. Repeatability is a relative measure of precision. However, for the reasons mentioned earlier, the Manipulator can never be expected to reach the target point exactly. The Manipulator actually achieves a range of positions some distance from the target. It is reasonable to expect that, over numerous attempts to hit a target, the actual output achieved will form a known statistical distribution.

Figure 4.3 illustrates the concept of probability distribution. This figure displays how the probability of achieving a desired output is distributed over a distance x. Each value of the ordinate p(x) gives the probability that the output will succeed in achieving a random position x. Probability distributions are an effective tool used to describe repeatability characteristics.

The most commonly used probability distribution used to interpret repeatability characteristics is the normal or Gaussian distribution. The equation for this distribution is:

$$P(x) = \frac{1}{S\sqrt{2\pi}}\, e^{-(x-\bar{x})^2/2S^2} .$$

where $\overline{X}$ is the arithmetic mean and S is the standard deviation as previously discussed.

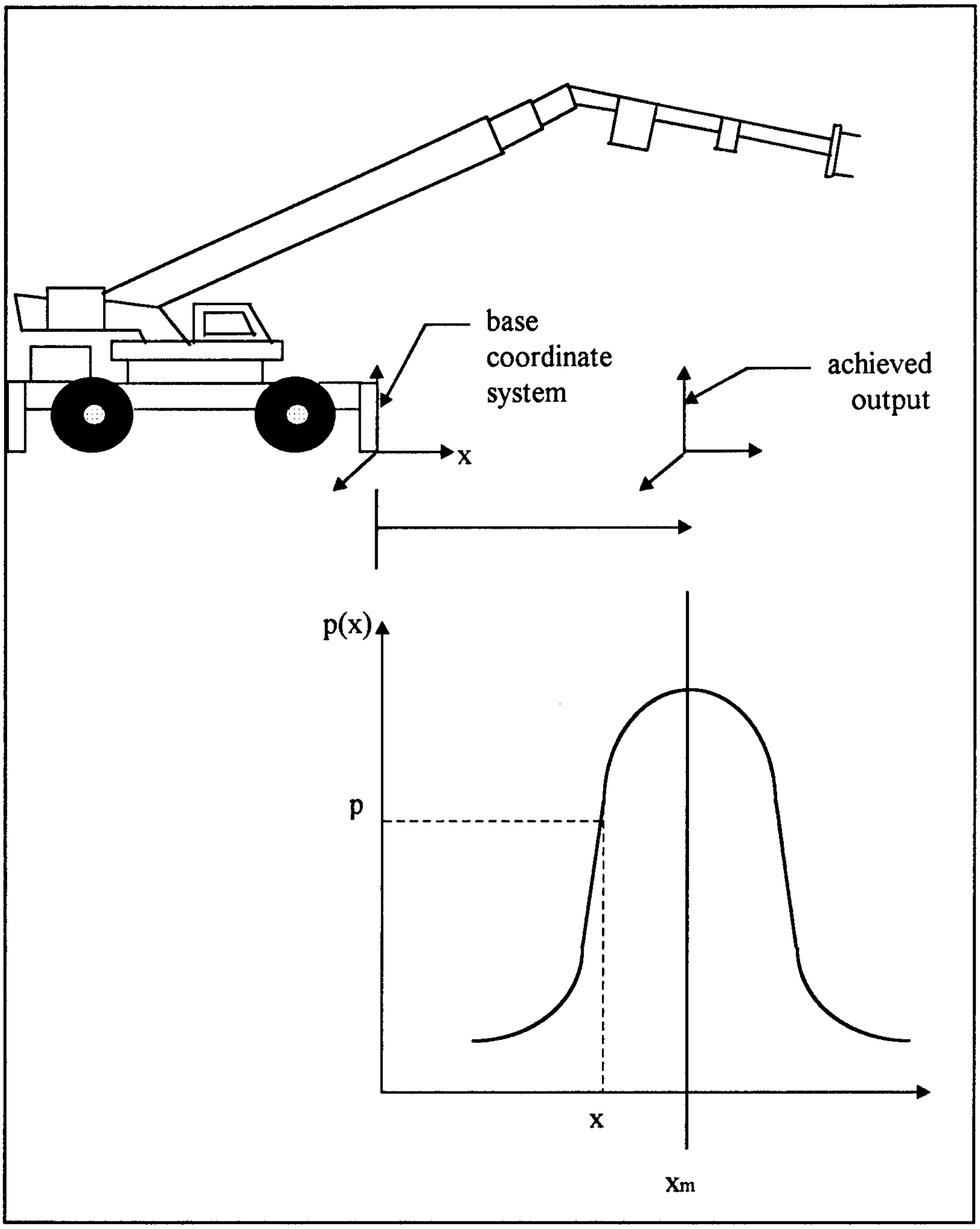


Figure 4.3 - Probability Distribution of Output

Figure 4.4 provides further illustration of the importance the probability distribution has on characterizing Manipulator output. Firstly, the original point taught to the Manipulator will not necessarily be the arithmetic mean. The position of the mean will be influenced by the manner in which the target was originally taught and later approached. Consequently, two distribution curves result from the two different directions of approach.

Secondly, with the use of probability distributions, it is possible to determine the likelihood that certain achieved outputs will fall within a specified deviation from the mean of the output. Calculating the probability that an output will fall within one, two and three standard deviations (*S*) of the mean will result in 68.27%, 95.45% and 99.73% respectively. Hence, it is possible to superimpose positional tolerances such that 99.73% of the output will fall within a specified band. Many robot suppliers often quote the width of this band as the repeatability of their robot (Appleton 1986).

And finally, the distance between the LHS and RHS distributions is called the mean hysteresis range, and the distance between three standard deviations is called the mean position variance. Care must be taken when programming the Manipulator to ensure that taught points are approached from the same direction (unidirectional repeatability). Use of a safe, approximate stand off point followed by a slow approach to the target will reduce the effects of mean position variance.

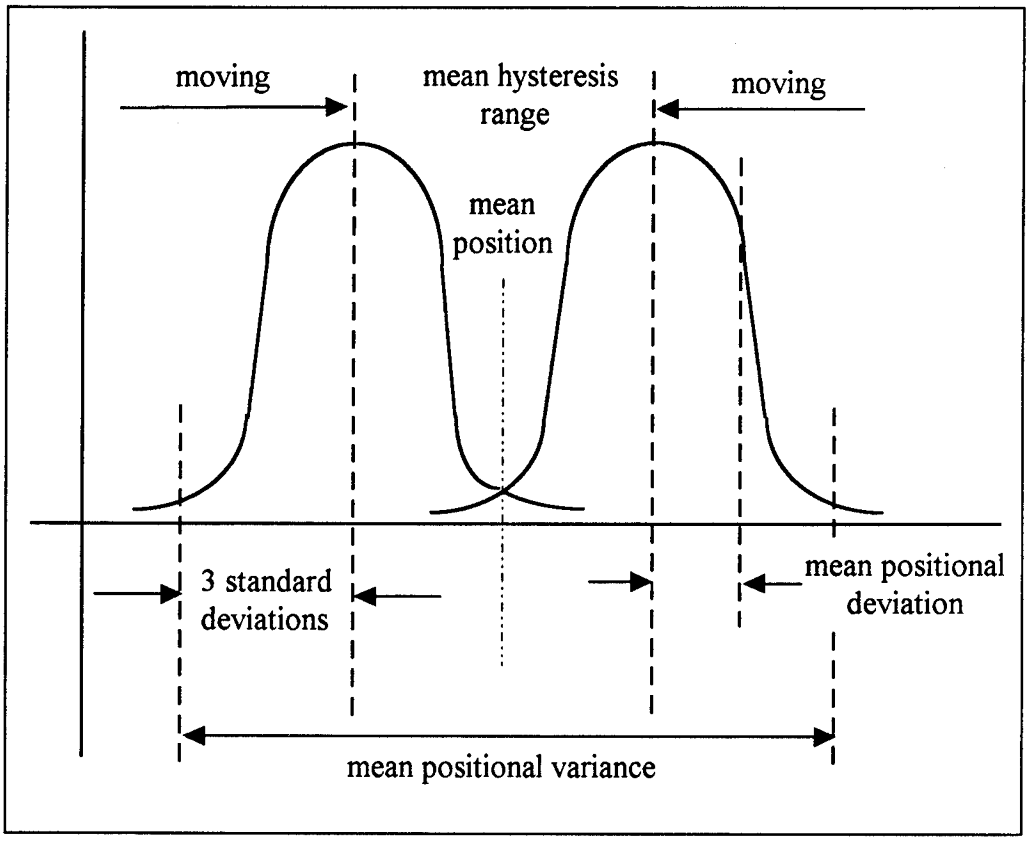


Figure 4.4 - Repeatability Characteristics (Appleton 1987)

CHAPTER FIVE

BENCHMARK TESTS FOR THE LARGE SCALE MANIPULATOR

The intent of this chapter is to define the benchmark test procedures for evaluating the performance criteria of Chapter 2. Methods of measuring the performance criteria are not discussed in this report. The reader is referred to chapter eight of Knopf (Knopf and Tesar, 1994) for information concerning robot metrology equipment.

The following performance tests are based on the American National Standard ANSI/RIA 15.01-1 90 for Point-to-Point and Static Performance and ANSI/RIA 15.01-2 92 for Path-Related and Dynamic Performance evaluations for industrial robots and robot systems. The static performance criteria are: accuracy, repeatability, cycle time, overshoot and settling time. For dynamic performance the criteria are: relative path accuracy, path repeatability, path speed characteristics and cornering overshoot. ANSI feels that these criteria represent the best indication of the overall static and path-related performance of industrial robots.

5.1 Coordinate Systems

This section establishes a common set of coordinate systems that describe the location of the Manipulator, end-effector and test data.

5.1.1 World Coordinate System

This coordinate system establishes a fixed frame of reference and is usually used to describe the workcell layout. This is a Cartesian coordinate system that consists of three translational coordinates (X_0,Y_0,Z_0) and three rotational coordinates (A_0,B_0,C_0). The translational coordinates form a right-handed coordinate system with the $+Z_0$ direction collinear with but opposite in direction to the gravity vector. The rotational coordinates are defined such that A_0, B_0 and C_0 rotate about the X_0, Y_0 and Z_0 axes respectively. Note that all rotation coordinates follow the right-hand rule convention (see Figure 5.1).

5.1.2 Base Coordinate System

The Base Coordinate System is used to establish the location of the Manipulator within the World Coordinate System. The Base Coordinate System defines the location of the standard test path and provides a frame of reference for recording test results. The Base Coordinate System is a Cartesian coordinate system that consists of three translational coordinates (X_1,Y_1,Z_1) and three rotational coordinates (A_1,B_1,C_1) comparable to the World Coordinate System.

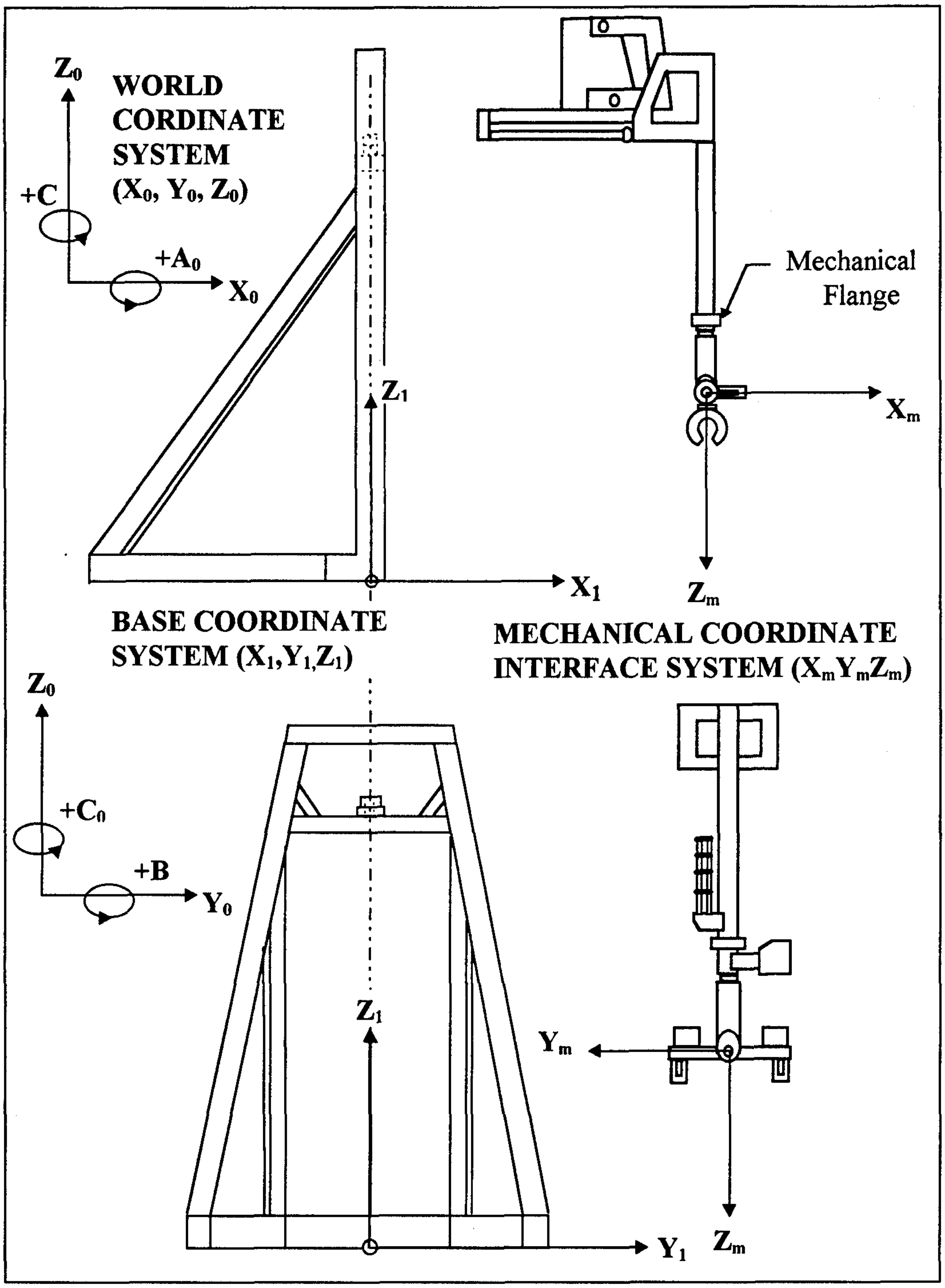


Figure 5.1 - Coordinate Systems

The origin of the Base Coordinate System is located at the intersection of the centerline of rotation of the first axis and the floor of the lab. The first axis is the first axis of motion encounter starting at the frame and progressing toward the end-effector. The $+X_1$ axis points away from the origin and continues through the centerpoint of the Manipulator working space (C_w) on the plane defined by the interface between the Manipulator's frame and the floor of the lab (see Figure 5.1).

The working space is the space in which the Manipulator has no limitations in the movement of the mechanical interface other than those imposed by the joints. The centerpoint (C_w) is the geometric center of that space (see Figure 5.2). The $+Z_1$ axis points in the direction of the mechanical structure of the Manipulator advancing away from the floor of the lab.

5.1.3 Mechanical Interface Coordinate System

The Mechanical Interface Coordinate System establishes the location of the end-effector relative to the Manipulator position. It is a Cartesian coordinate system that consists of three translational coordinates (X_m,Y_m,Z_m) and three rotational coordinates (A_m,B_m,C_m) comparable to the World and Base Coordinate Systems.

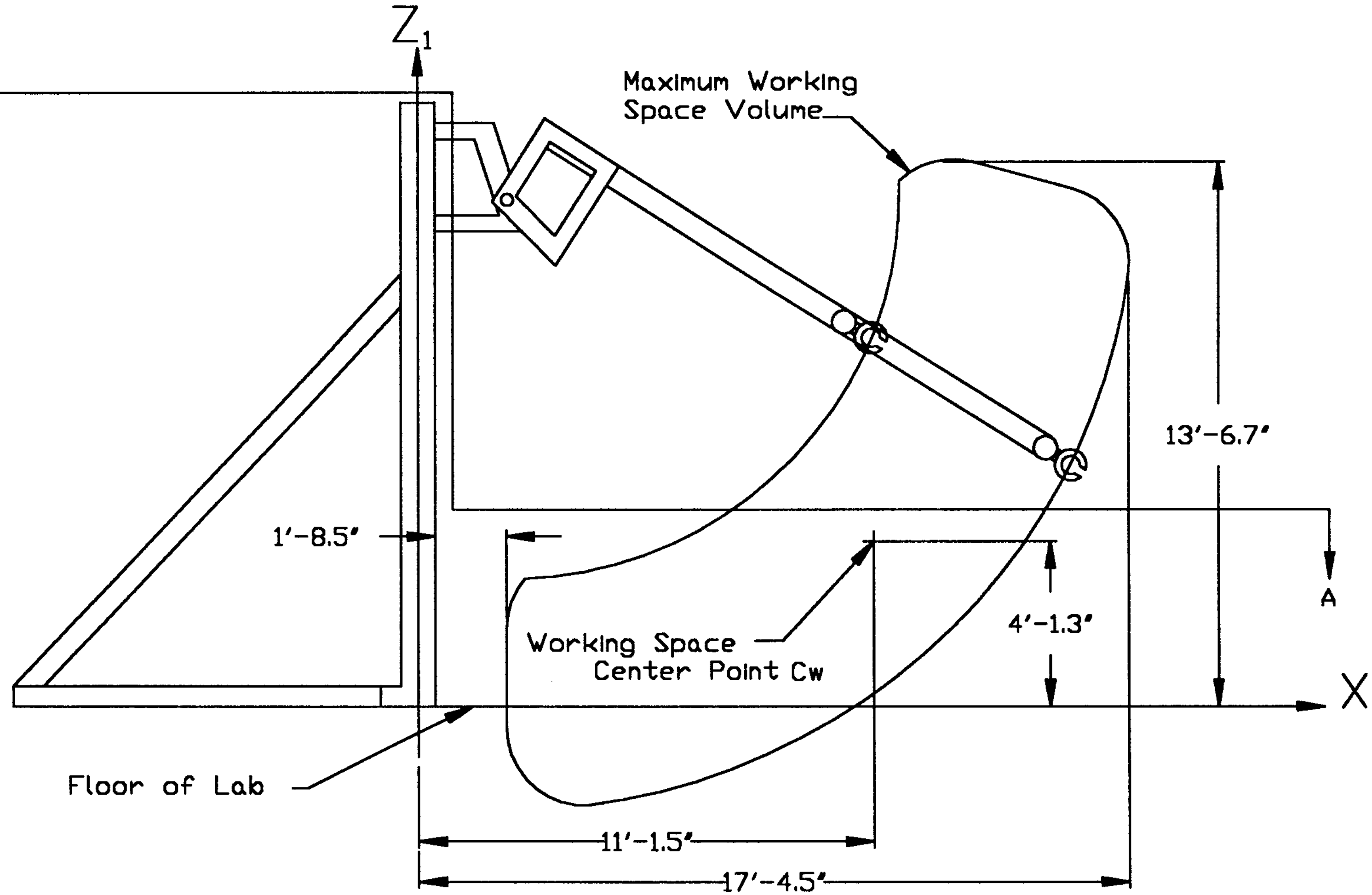
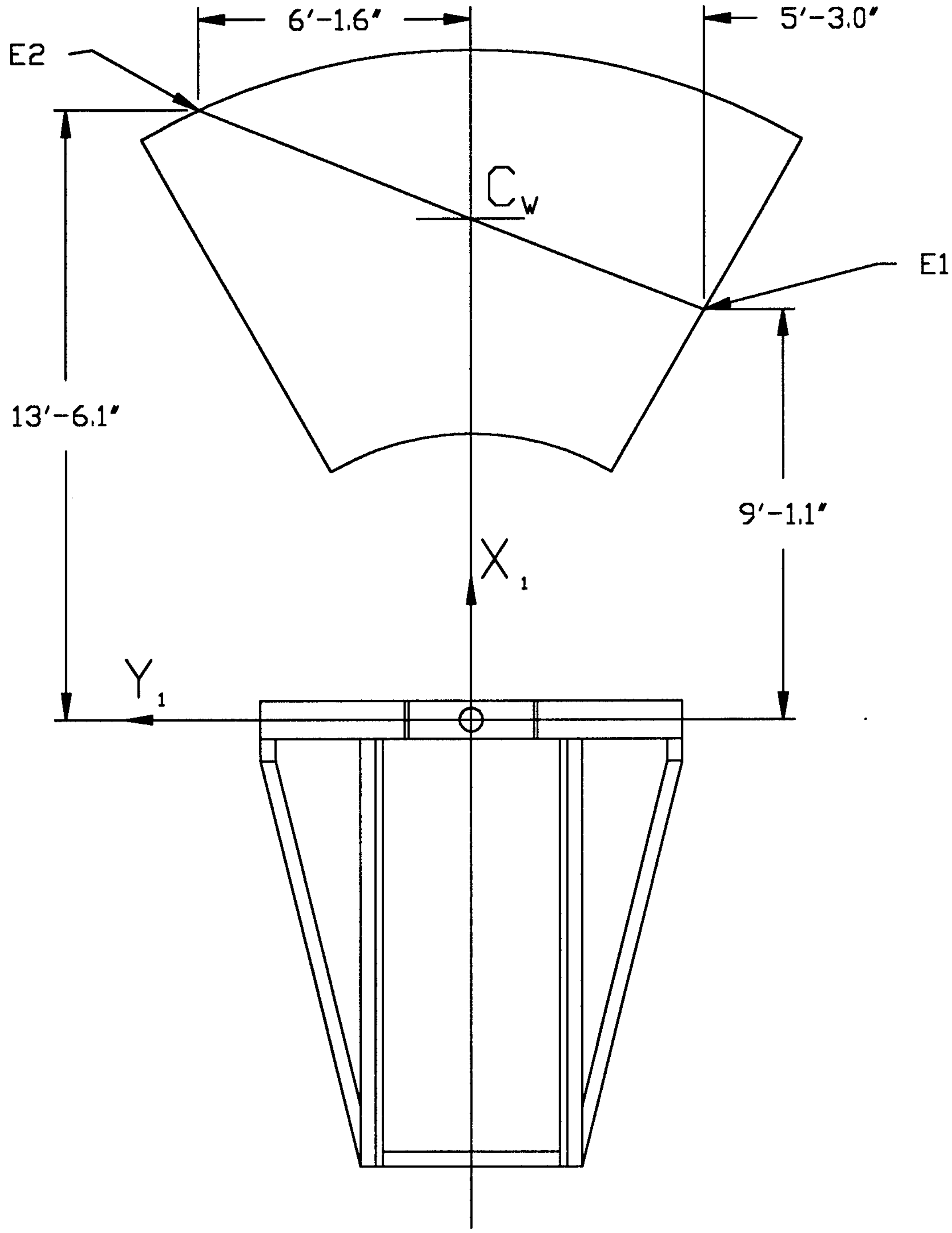


Figure 5.2a Working Space Volume



Section A-A

Figure 5.2b - Reference Center Line E1E2

The origin of the Mechanical Interface Coordinate System is located at the intersection of the Manipulator's Roll, Pitch and Yaw axes in their mid-positions (see Figures 5.1 and 5.3). The $+Z_m$ axis is defined by the centerline of the Roll axis and points outwardly normal to the mechanical flange of the Manipulator. The $+X_m$ axis is defined by the centerline of the Yaw axis and points away from the $+Z_1$ axis. The $+Y_m$ direction is defined by the right-hand rule coordinate system convention.

5.1.4 Test Equipment Coordinate System

The Test Equipment Coordinate System establishes the direction of the sensor output. It is a Cartesian coordinate system that consists of three translational coordinates (X_t,Y_t,Z_t) and three rotational coordinates (A_t,B_t,C_t) comparable to the other systems. The (X_t,Y_t,Z_t) coordinates form a right-handed coordinate system with the origin established by the measurement apparatus. The vector relationship between the Base Coordinate System and the Test Equipment Coordinate System shall be recorded with the test output.

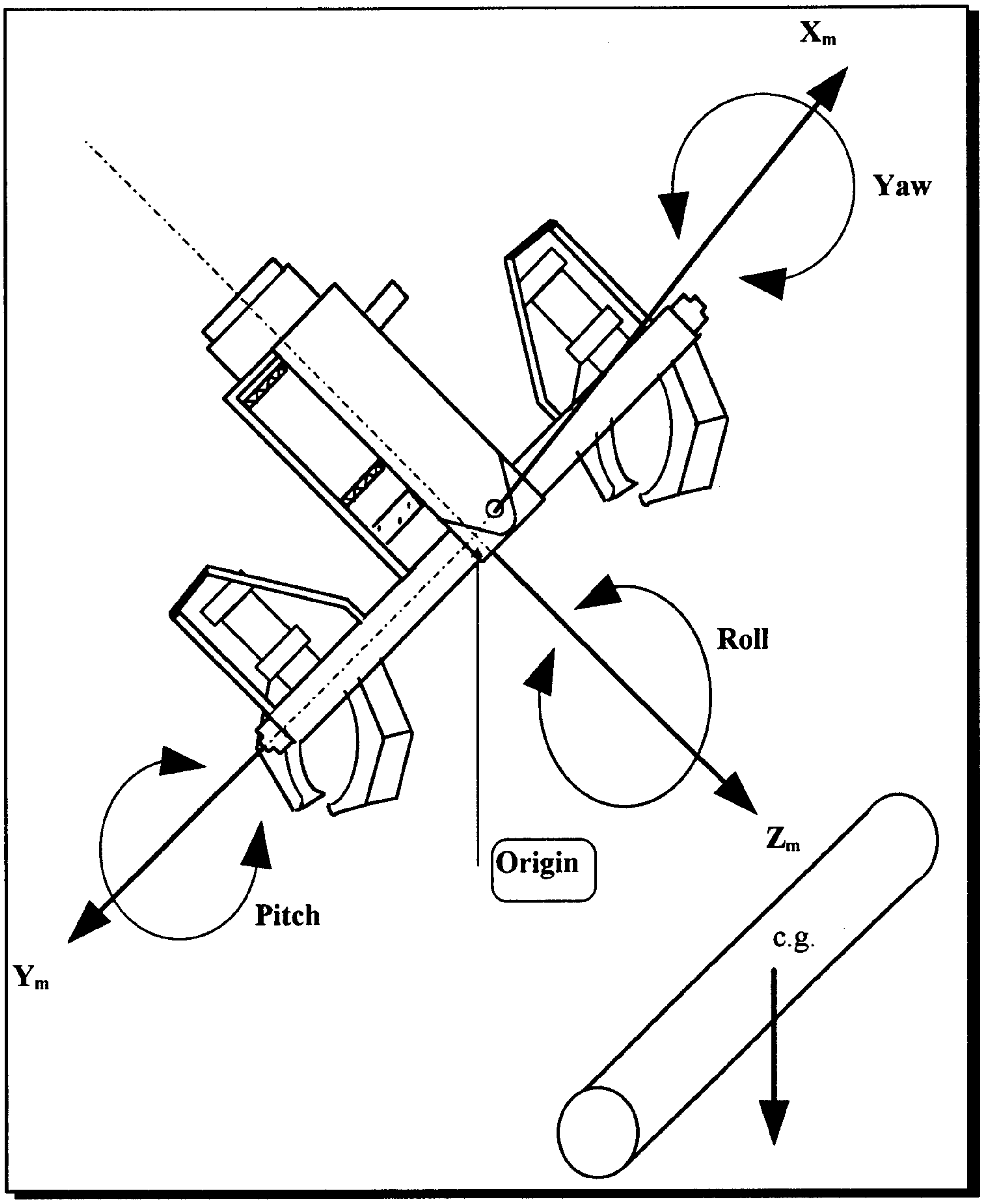


Figure 5.3 - Mechanical Interface Coordinate System

5.2 Standard Test Conditions

ANSI recommends the following conditions under which the standard test should be performed.

5.2.1 Test Environment

The environment shall be maintained at the following conditions:

1. The ambient temperature shall be 18°C to 30°C and be maintained within a total range of 2°C.

2. The relative humidity shall be maintained between 30 and 90%.

3. The vibration content shall be measured and noted if believed to significantly affect the test results.

These test conditions shall be noted with the test results.

The intent of these rigid test conditions is to achieve consistent performance. It is important to ascertain the Manipulator's full performance potential. Obviously these conditions will not be met during outside crane mounted testing. Regardless, the environment conditions shall always be noted.

5.2.2 Test Load

The rated payload of the Manipulator is greater than 140 kg and thus falls into ANSI Standard Test Load Category 12. For this class, ANSI recommends a payload of no less than 50% of the manufacturer's maximum rated specification. Since the Manipulator's maximum payload is currently 1600 lbs. (725 kg), the standard test load shall be no less than 800 lbs. (363 kg). The weight, moment and inertial properties of the test load shall be recorded.

5.2.3 Test Point

The test point is the physical point on the end-effector where the Manipulator position is measured. Per ANSI recommendations, the test point shall be located as close as possible to, but not necessarily coincident with, the center of gravity of the test load. The axial and radial offset of the test point will be greater than or equal to the axial and radial offset of the test load center of gravity. The following definitions apply:

- *axial offset.* The distance along the Z_m axis of the Mechanical Interface Coordinate System to the center of gravity of the test load.

radial offset. The perpendicular distance from the Z_m axis of the Mechanical Interface Coordinate System to the center of gravity of the test load (see Figure 5.3).

5.2.4 Test Plane

The test plane is an unbounded referenced plane within the Manipulator working space that is parallel to the (1, 1, -1) plane and passes through the working space center point, C_w (see Figure 5.4). The test path lies within the test plane.

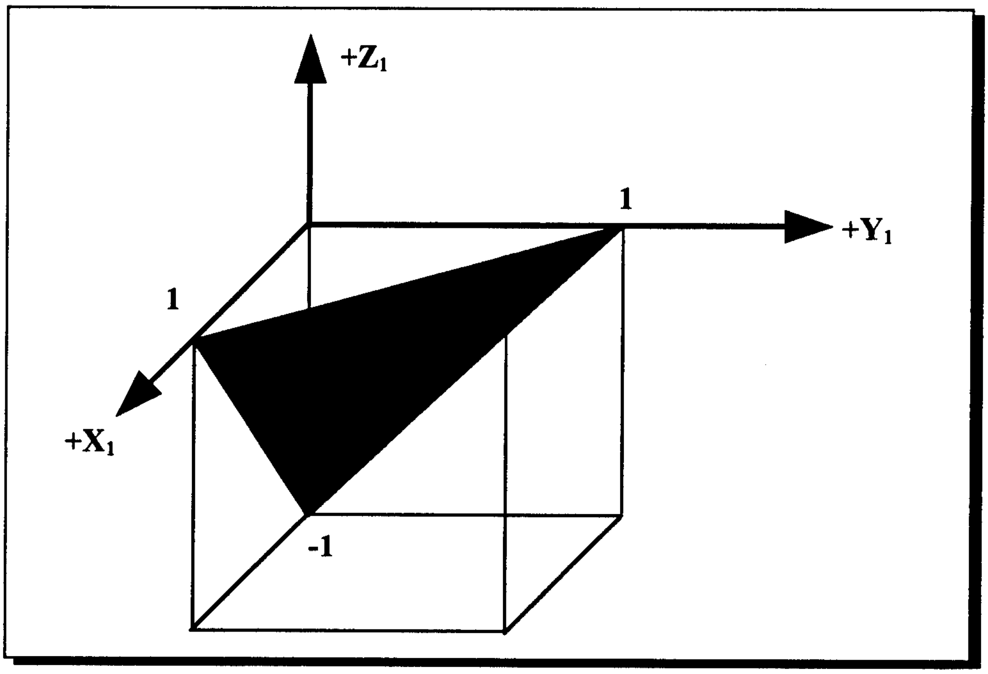


Figure 5.4 - Test Plane Location (ANSI/RIA R15.05-1 90)

5.2.5 Test Path

The test path is a sequence of points used to quantify the performance of the Manipulator. The test path specified by ANSI allows for the relative comparison of accuracy, repeatability, cyclic rate and overshoot between different large scale manipulators. All data shall be taken from measurements of motion along the test path. The specific measurements that quantify the test paths for static and dynamic testing are described in the following sections.

5.2.5.1 Static (Point to Point) Test Path

This test path is adopted from ANSI/RIA R15.05-1 90. The path is located in the test plane and lies along the reference center line E_1E_2 (see Figure 5.2b). Points E_1 and E_2 are located at the intersection of the test plane and the boundary of the Manipulator working space on a horizontal line that passes through the working space center point, C_w.. The test path (Figure 5.5) is defined as:

1. A rectangle located in the test plane with L_1, U_1, U_4 and L_4 forming the corners.

2. The test path segment length (S_L) will be 1000 mm, the largest test segment recommended by ANSI. The path will contain at least three segments.

3. The rectangular segment side lengths (D_L) will be one-half the path segment length (S_L) or 500 mm.

4. The total length of the test path rectangle is defined as the length of the line F_1F_2 (3000 mm). The segment end-points are labeled U_1 through U_4 along the top (line U_1U_4) and L_1 through L_4 along the bottom (line L_1L_4).

5. The length of line segments E_1F_1 and E_2F_2 will be equal.

6. The Manipulator shall maintain, where possible, the orientation of the Mechanical Interface axis Z_m perpendicular to the test plane at all points. Where the limiting range of the pivoting motion precludes this (Glass 1984), the Manipulator shall maintain the Z_m axis as near to perpendicular to the test plane as possible.

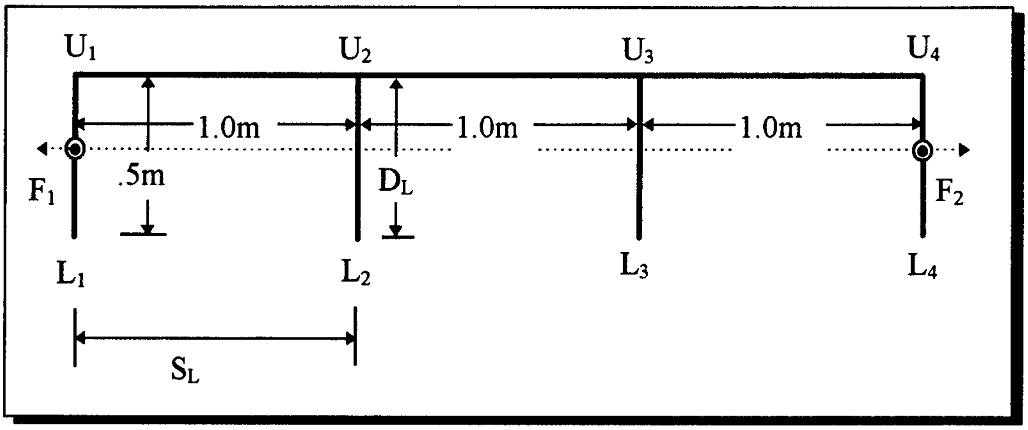


Figure 5.5 - Static Test Path (lab tests)

5.2.5.2 Dynamic (Path-Related) Test Path

This test path is adopted from ANSI/RIA R15.05-2 92. The path is located in the test plane and lies along the reference center line E_1E_2 (see Figure 5.2b). Points E_1 and E_2 are located at the intersection of the test plane and the boundary of the Manipulator working space on a horizontal line that passes through the working space center point, C_w.. The test path (Figure 5.5) is defined as:

1. A rectangle such that the path motions result in the Manipulator moving the test load through a large area of the Manipulator's working space.

2. The center of the rectangle will be the midpoint, C_p, of the center line E_1E_2.

3. The rectangle will be defined (see Figure 5.6) by the four corner points (R_1, R_2, R_3, R_4).

4. The segment lengths, S_L, shall be 1000mm as recommended by ANSI.

5. The rectangle will have a height of S_L (1000mm) and a length of $2S_L$ (2000mm).

6. The direction of travel will be clockwise when viewed from the base of the Manipulator.

7. The starting point will be as shown in Figure 5.6.

8. ANSI recommends a maximum speed of 1000mm/sec for an S_L=1000mm.

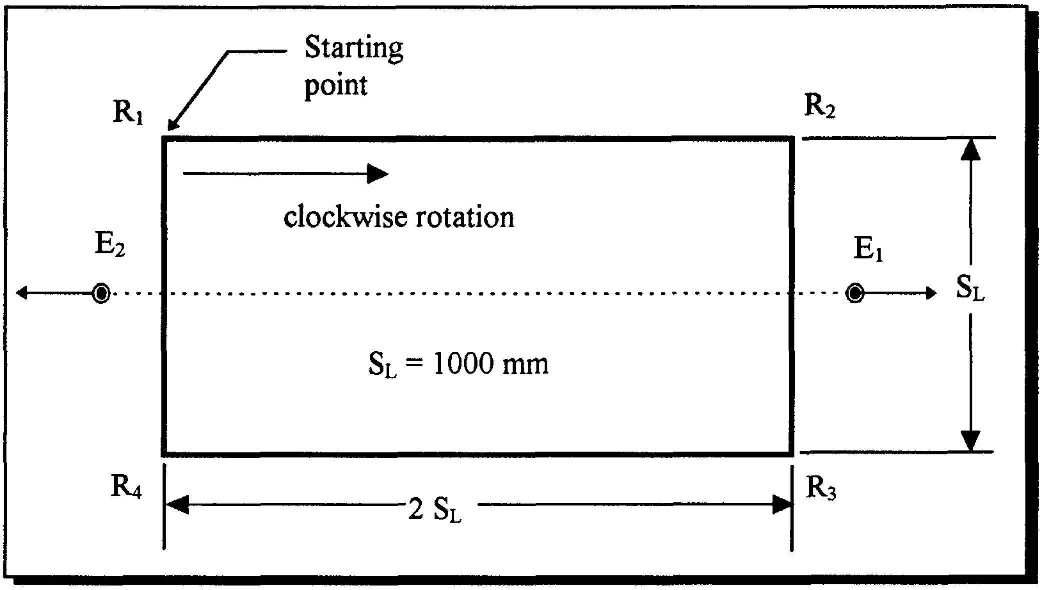


Figure 5.6 - Dynamic Test Path (lab tests)

5.2.6 Working Space Center Point

The working space center point, C_w, of the Manipulator is located at the midpoint of the line parallel to the X_1 axis whose Z_1 axis position will be the midpoint of travel in the Z_1 axis direction (see Figure 5.2).

5.2.7 Path-Related Evaluation Planes

ANSI (ANSI/RIA R15.05-2 92) introduces the concept of evaluation planes to simplify the calculation process by transforming complex three-

dimensional path calculations into the intersections between the attained path and the two-dimensional evaluation planes (see Figure 5.7). Evaluation planes are used to establish discrete locations for the evaluation of path accuracy and repeatability. These planes are aligned normal to the test plane and are placed at equal linear distances of 1/4 S_L apart (250 mm). There are a total of 20 evaluation points. Linear interpolation shall be used when an attained point does not lie exactly on the evaluation plane (see Figure 4.2).

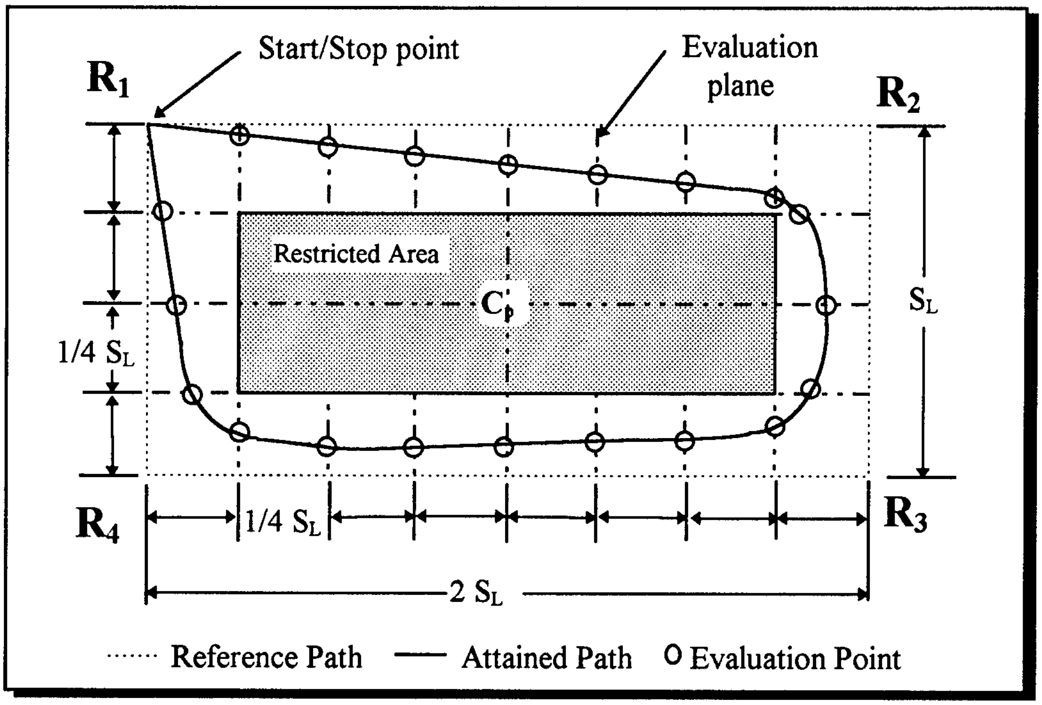


Figure 5.7 - Path Related Evaluation Planes

5.3 Performance Classes

ANSI provides different performance classes for optimizing specific performance characteristics (for example, repeatability or cycle time). Hardware and software adjustments can be made prior to testing for each performance class. However, all adjustments must remain constant for every test within the performance class. The four classes are:

- *Class I- Standard :* To evaluate overall performance without optimizing specific parameters. The standard test conditions were outlined in the previous section. Per ANSI guidelines, the Manipulator, a hydraulic system, may be operated for 15 minutes prior to data acquisition. The Manipulator shall not experience system overloads or overheating during testing.

- *Class II - Cycle Time (Speed) :* To evaluate the Manipulator under optimized cycle time conditions. Performance parameters may be varied to enhance cycle time performance consistent with intended use but still remain indicative of actual cycle time performance.

- *Class III - Repeatability:* To evaluate the Manipulator under optimized repeatability conditions. Performance parameters may be varied to enhance

repeatability performance consistent with intended use but still remain indicative of actual repeatability performance.

- *Class IV - Special:* To evaluate other specific Manipulator performance characteristics. This class is provided to allow testing of characteristics not covered in classes I through III.

5.4 Performance Criteria for Point to Point and Static Testing

This section outlines the static and point to point performance criteria of the Manipulator. The following subsections are derived from ANSI/RIA R15.05-1 90.

5.4.1 Positional Accuracy (PA)

ANSI defines static positional accuracy as the statistical measure of the spatial deviation between commanded and achieved Manipulator positions. The static accuracy will be computed from the data collected during operation of the Manipulator under the standard test conditions outlined in section 5.2. The recommended procedure is:

1. Calibrate the Manipulator control system. Enter the coordinates of the test point into the controller.

2. Match the Test Equipment Coordinate System with the Base Coordinate System at three or more points along the test path.

3. Enter the commanded poses into the Manipulator controller without physically moving the Manipulator. The list of poses will consist of unique commanded poses (for example X_1, Y_1, Z_1, A_1, B_1, C_1). The (X_1, Y_1, Z_1) coordinates will be identical to the test path vertices described in section 5.2.5.1. The orientation coordinates (A_1, B_1, C_1) shall be selected at random from the set of all achievable positions. Fifty poses will be input to the controller using multiple visits to each vertex.

4. Command the Manipulator to stop at the selected commanded poses. The order of visiting each vertex shall be completely random to provide unique approach paths. After the Manipulator has reached stabilization, measure the achieved pose in the test equipment coordinates (X_t, Y_t, Z_t).

5. Compute the mean ($\bar{d}_{pa}$) and standard deviation (S_{PA}) accuracy as described in Section 4.2.1 and record results.

5.4.2 Positional Repeatability

ANSI defines positional repeatability as the measure of deviation between achieved Manipulator positions and the mean of those positions after ordering the Manipulator to the same pose N times. The repeatability will be computed from the data collected during operation of the Manipulator under the standard test conditions outlined in section 5.2. The recommended procedure is:

1. Three measurement positions are required and will consist of the L_1, L_2, and L_4 positions shown in Figure 5.5. The motion between these measurement positions will be along the test path while maintaining the orientation of the mechanical interface.

2. Warm-up drift and the warm-up period are determined from the number of readings that elapse, after a cold start, until the system reaches system stabilization. Warm-up drift is the positional difference between the first position after start-up and the first position after reaching system stabilization. The warm-up period is the time this takes measured in minutes.

3. Calculate and record the Manipulator's mean positional repeatability ($\overline{d}_{REP}$) and standard deviation (S_{REP}) as described in Section 4.2.3 for a recommended sample size (N) of 500 continuous cycles.

5.4.3 Cycle Time

Segment time and traverse cycle time are the two figures recorded for cycle time.

- *Segment cycle time* is the average time required by the Manipulator to travel through one segment of the test path and is recorded in seconds.
- *Traverse cycle time* is the average speed attained while completing relatively large movements.

The recommended procedure is:

1. The test load and test path previously described in section 5.2 shall be used.

2. During the segment cycle portion of the test, the Manipulator shall be programmed to following test path:

$$L_1 \rightarrow U_1 \rightarrow U_2 \rightarrow L_2 \rightarrow U_2 \rightarrow U_3 \rightarrow L_3 \rightarrow U_3 \rightarrow U_4 \rightarrow L_4.$$

The start and end points of each segment are the points labeled L. The Manipulator shall reach system stabilization at each point before continuing.

3. Upon reaching point L_4, the Manipulator shall return to L_1 using the following return path: $L_4 \rightarrow U_4 \rightarrow U_1 \rightarrow L_1$. This is the path for measuring the traverse speed.

4. The Manipulator shall maintain the orientation of the mechanical interface axis, Z_m, throughout the test. The maximum deviation for the programmed upper point (U_1, U_2, U_3, U_4) shall be recorded.

5. Compute segment cycle time as follows:

$$\text{segment cycle time} = \frac{\text{Time }(L_1 \text{ to } L_4)}{3} \text{ seconds/segment}$$

where Time(L_1 to L_4) is the time required to travel from L_1 to L_4 in step 2. Segment time is the average number of seconds required to move through one segment. The total number of segments in this test path is three.

6. Compute average traverse speed as follows:

$$\text{average traverse speed} = \frac{3(S_L) + 2(D_L)}{\text{Time}(L_4 \text{to} L_1)} \text{ meters/second.}$$

Average traverse speed is the average speed achieved during step 3.

5.4.4 Overshoot and Settling Time

Overshoot is measured to quantify the Manipulator capability to make smooth and accurate stops. Overshoot is an important performance parameter for operations involving large inertia's, high speed or frequent stops. To measure

overshoot the Manipulator is run continuously from $U_1 \rightarrow L_1 \rightarrow U_1 \rightarrow U_2 \rightarrow L_2 \rightarrow U_2 \rightarrow U_3 \rightarrow L_3 \rightarrow U_3 \rightarrow U_4 \rightarrow L_4 \rightarrow U_4$ and then straight to U_1 (see Figure 5.5). Overshoot is equal to the overtravel distance at point L_1 and is an absolute value along the direction of points U_1 to L_1 when the Manipulator approaches from point U_1. Overshoot shall be measured for several cycles and the average recorded.

Settling time is measured to quantify the Manipulator's capability to stop quickly at a target point. To measure settling time, the Manipulator is run through the same cycle as overshoot. When the Manipulator approaches point L_1 from U_1 the position of the test point is continuously measured until system stabilization reached. Settling time is measured as the elapsed time from the instance of initial crossing into the limit band until the instance when the Manipulator remains within the limit band (see Figure 2.4). Repeat the same procedure several times and record the average value.

5.5 Performance Criteria for Path-Related and Dynamic Testing

This section outlines the path-related and dynamic performance criteria of the Manipulator. The following subsections are derived from ANSI/RIA R15.05-2 92.

5.5.1 Relative Path Accuracy

ANSI defines relative path accuracy as the measurement of the distance between a reference path and any given attained path. The relative path accuracy test utilizes a previously measured path as reference. The reference path is acquired by commanding the Manipulator to follow the standard test path at the standard test conditions described in Section 5.2. The recommended procedure is:

1. Calibrate the Manipulator control system. Enter the coordinates of the test point into the controller.

2. Move the Manipulator such that the test point coincides with the midpoint, C_p, of the test plane. The C_p is used as the origin of the coordinate system defining the reference path. The Test Equipment Coordinate System is aligned with the test plane per Section 10.2.3.3 of ANSI/RIA R15.05-2 92.

3. Program the Manipulator to follow the test path described in Section 5.2 at a speed of 100mm/sec. Measure the (Xr_j, Yr_j, Zr_j) points (see Figure 4.1) for each of the *m* evaluation points shown in Figure 5.6. Use linear interpolation to calculate the intersection of the relative reference path with the evaluation plane (see Figure 4.2). These values will be used as the reference path to measure relative path accuracy.

4. Program the Manipulator to follow the standard test path at 50% and 100% of maximum speed. Measure the attained (Xr_j, Yr_j, Zr_j) coordinates for each evaluation point.

5. Calculate the maximum path accuracy (AC_{REL}) and the average path accuracy ($\overline{AC}_{REL}$) as described in Section 4.2.2 and record the results.

5.5.2 Path Repeatability

ANSI defines path repeatability as the measure of the closeness between multiple attained paths. Path repeatability is measured using the same test procedure described in Section 5.5.1 above. The difference between the measured path accuracy and path repeatability is that path repeatability uses the average of a path traversed *n* times (see Section 4.2.4). Calculate the maximum path

repeatability (PR) and average path repeatability ($\overline{PR}$) as described in Section 4.2.4.

5.5.3 Path Speed Characteristics

ANSI defines four terms to quantify path speed characteristics:

1. *Path speed accuracy* (AS) : the difference between the programmed speed and the mean value of the attained speed during *n* traversals along the test path. AS is expressed as a percentage of the programmed speed:

$$AS(\%) = \left[\frac{\bar{s} - \bar{s}_p}{s_p}\right] \times 100 \quad \text{where, } \bar{s} = \frac{1}{n}\sum_{i=1}^{n}\bar{s}_i, \quad \text{and} \quad \bar{s}_i = \frac{1}{m}\sum_{j=1}^{m}s_{ij}.$$

Here:

$\bar{s}_p$ is the programmed speed;

s_{ij} is the attained speed for the *i*th cycle and *j*th evaluation point;

m is the number of evaluation points;

n is the number of cycles;

$\bar{s}$ is the mean speed for one traversal of the test path.

2. *Path speed Repeatability* (RS): the closeness of agreement of the speeds attained for the same programmed speed. Using the same procedure as path speed accuracy:

$$RS(\%) = \left[\frac{\bar{s}}{s_p}\right] \times 100.$$

3. *Path speed fluctuations* (FS): the maximum deviation in speed for a single traversal of an attained path at constant speed conditions. Using the same procedure as path speed accuracy:

$$FS = \max_{i=1}^{n}\left[\max_{j=1}^{m}(s_{ij}) - \min_{j=1}^{m}(s_{ij})\right].$$

4. *Path acceleration time* (TS): the time to move from zero speed to programmed speed. The time interval is measured from the first detection of motion to the point where the Manipulator attains the average speed within the tolerance defined by the path speed fluctuation (FS).

5.5.4 Cornering Overshoot

ANSI defines corner overshoot (CO) as the maximum deviation past the target. It is measured as the largest deviation outside the reference path after the Manipulator has "passed" a corner. The value of CO can be calculated for each of the three corners traversed in the standard test path. The equation for CO is:

$$CO = \max_{k=1}^{k} \sqrt{(X_{ak} - X_{rk})^2 + (Y_{ak} - Y_{rk})^2 + (Z_{ak} - Z_{rk})^2}.$$

Where:

- X_{ak}, Y_{ak}, Z_{ak} are the position coordinates on the attained path;
- X_{rk}, Y_{rk}, Z_{rk} are the coordinates along the reference path;
- k is the subscript number for each of the discrete data points along the path and is dependent upon the test equipment sampling rate (see ANSI/RIA R15.05-2 92 for further explanation).

CHAPTER SIX

CONCLUSIONS

This report presents various methods of performance qualification for large scale construction manipulators for the purpose of ascertaining physical specifications. The report defines the most important static and dynamic performance criteria and presents a method for evaluating them. These criteria are accuracy, repeatability, overshoot, settling time and cycle time.

A set of meaningful benchmark tests are presented to gauge the overall static and dynamic performance of different large scale manipulators in order to provide a means of relative comparison. These performance tests are based on the American National Standard ANSI/RIA 15.01-1 90 for Point-to-Point and Static Performance and ANSI/RIA 15.01-2 92 for Path-Related and Dynamic Performance Evaluations of industrial robots and robot systems.

Statistical methods are included for calculating the probability that the Manipulator will achieve a desired target within a calculated standard deviation. The formulas for computing position accuracy, repeatability and their respective standard deviations are reviewed for both static and path-related output.

Finally, the report reviewed the application of human factors engineering and presented a method to quantify potential improvements to the human-machine interface.

The large scale manipulator owned by the University of Texas is a very adaptable machine. Its eight degrees-of-freedom, sixty-five foot working radius and multi-functional potential make it a noteworthy test bed for developing enhanced control and performance testing strategies. With the application of these benchmark tests, a means of comparing the relative strengths and weaknesses of different controllers and manipulators can begin.

BIBLIOGRAPAHY

Adams J.A., "Human Factors Engineering". MacMillian, NY., 1989.

American National Standard Institute, "Path-Related and Dynamic Performance Characteristics-Evaluation" *ANSI/RIA R15.05-2-1992*, ANSI, 1993.

American National Standard Institute, "Point-to-Point and Static Performance Characteristics-Evaluation" *ANSI/RIA R15.05-1-1990*, ANSI, 1990.

Appleton E., and Williams, D.J., "Industrial Robot Applications". Halmsted Press, NY., 1987.

Ardayfio, David D., "Fundamentals of Robotics". Marcel Dekker, NY., 1987.

Colson, James C., "Performance Measures for Robotic Systems". Thesis, December 1984. The University of Texas

Dhillon, B.S., "Robot Reliability and Safety". Springer-Verlag, NY., 1991.

Engelberger, J.F., "Robotics in Practice". AMACOM, 1980.

Fisher, D.J., "Piping Erection Constructability Issues in a Semi-Automated Environment". Dissertation, May 1989. The University of Texas at Austin.

Glass, Clinton C., "The Pipe Manipulator: A Complete Assessment of a New Idea in Construction Equipment Technology". Thesis, December 1984. The University of Texas at Austin.

Graham, J.H., (editor), "Safety, Reliability, and Human Factors in Robotic Systems". Van Nostrand Reinhold, NY., 1991.

Holman, Jack P., "Experimental Methods for Engineers". McGraw-Hill, 1984.

Hudgens, Jeffery C. and Tesar D., "Static Robot Compliance and Metrology Procedures with Application to a Light Machining Robot". August 1992. The University of Texas at Austin.

Hsieh, Ting-Ya, and Haas, Carl T., "Applications of Large-Scale Manipulators in the Construction Environment" *Automation and Robotics in Construction X*, (edited by Watson, Tucker and Walters), Elsevier, NY, 1993, pp. 55-62.

Hughes, Peter J., "Construction Manipulator Teleoperation with Ergosticks". Dissertation, May 1990. The University of Texas at Austin.

Knopf, A.C. and Tesar, D., "A Roadmap for Modular Robot Metrology". December 1994. The University of Texas at Austin.

Mehrez, A. and Offodile, O.F., "A Statistical-Economic Framework for Evaluating the Effect of Robot Repeatability on Profit" *IIE Transactions*. May 1994, pp.101-110.

Nof, S.Y., "Robot Ergonomics: Optimizing Robot Work" *Handbook of Industrial Robots*, (edited by Nof), Wiley & Sons, NY, 1985, pp.549-604.

Olex, M.B. and Shulman, G.G., "Human Factors Effort in Robotic Systems Design" *Proceedings of the 13th International Symposium on Industrial Robots and Robot Systems*. April 7, 1983, pp. 9.29-9.36.

Sanders M.S. and McCormick E.J., "Human Factors in Engineering and Design" *(7th edition)*. McGraw-Hill, NY., 1993.

Thomas, Geoffrey A., "Development of an Advanced Control System for the University of Texas Large Scale Hydraulic Manipulator". Thesis, Spring 1995. The University of Texas at Austin.

Todd, D.J., "Fundamentals of Robot Technology". Wiley, NY., 1986.

Warnecke, H.J., Schraft, R.D. and Wanner, M.C., "Performance Testing" *Handbook of Industrial Robots*, (edited by Nof), Wiley & Sons, NY, 1985, pp.158-166.

Wodzinski, M. "Putting Robots to the Test". *Robotics Today*. June 1987, pp.17-20.

VITA

Mark Edward Wiersma is a native of Cleveland, Ohio. [redacted] the son of Rita and Edward Wiersma. After earning his diploma from St. Edward High School, Lakewood, Ohio, in 1984, he enrolled at Cleveland State University and began his quest for an engineering degree.

During the summers of 1986, 1987 and 1988 he was an active participant in the Cooperative Education Program and accumulated over twelve months of work experience at several manufacturing plants. After this brief introduction, he applied for and accepted a Civil Engineer Corp "Exceptional Student" scholarship from the United States Navy. He received his Bachelor of Mechanical Engineering degree in June 1989.

His first assignment as a newly commissioned officer was on board Naval Mobile Construction Battalion 133 homeported in Gulfport, MS. During his tour with NMCB 133, he was assigned the duties of Engineering Officer, Material Liaison Officer and Assistant Company Commander. He deployed to Iraq for Operation Provide Comfort following the Persian Gulf War. In March 1992, he became the Officer in Charge of Construction Battalion Unit 418 at Naval Submarine Base Bangor.

In September 1994, he entered the Graduate School at the University of Texas under the Navy's Fully-Funded Graduate Education Program. He is a Registered Engineer in Training in the State of Ohio.

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This report was typed by the author.